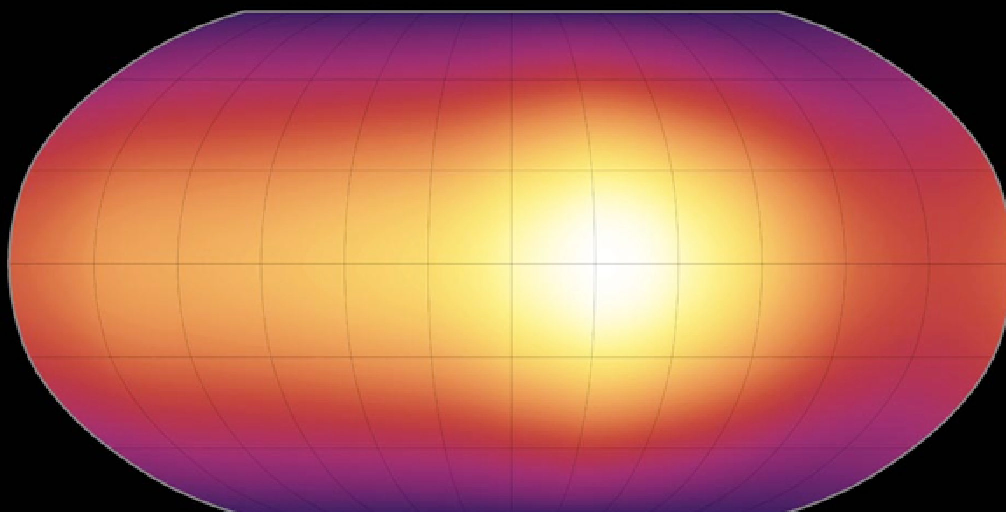
"Mapping" Exoplanets with Spitzer



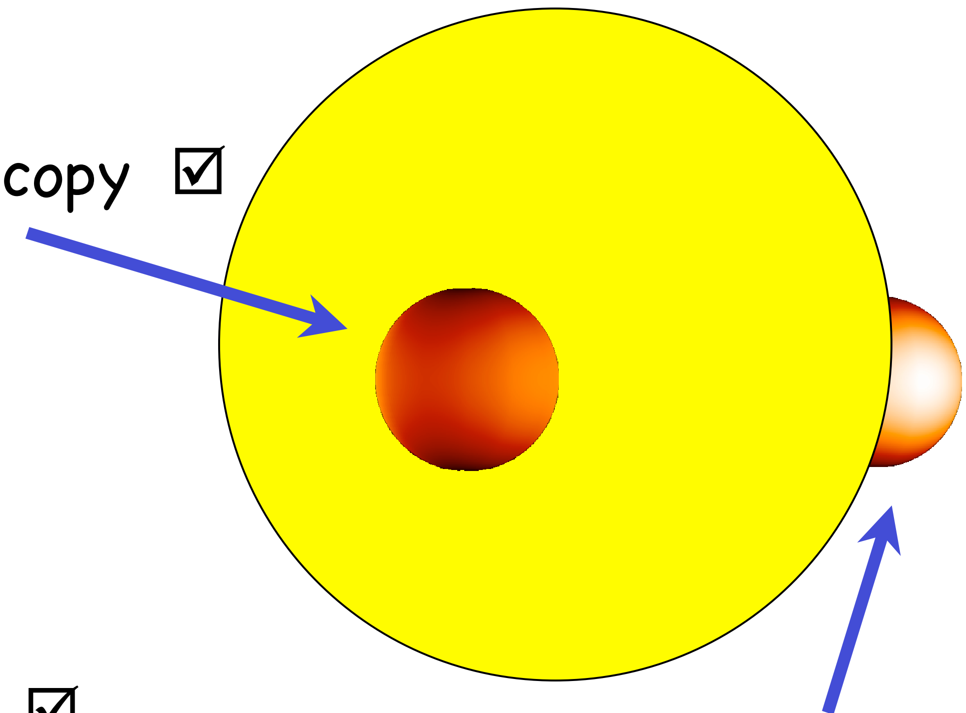
Eric Agol (University of Washington)

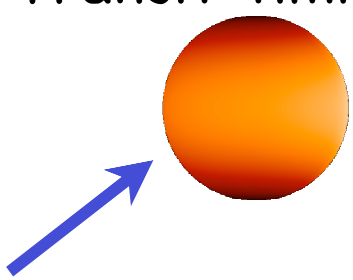
N. Cowan (UW), H. Knutson, D. Charbonneau (CfA), A. Showman, C. Cooper (UA), J. Fortney (UCSC), G. Henry (TSU), L. Allen (CfA), M. Everett (PSI), T. Megeath (Toledo)

Probing Planets

Transits

- Mass-radius relation
- Transmission spectroscopy ☑
- Transit timing





IR Phase Curves

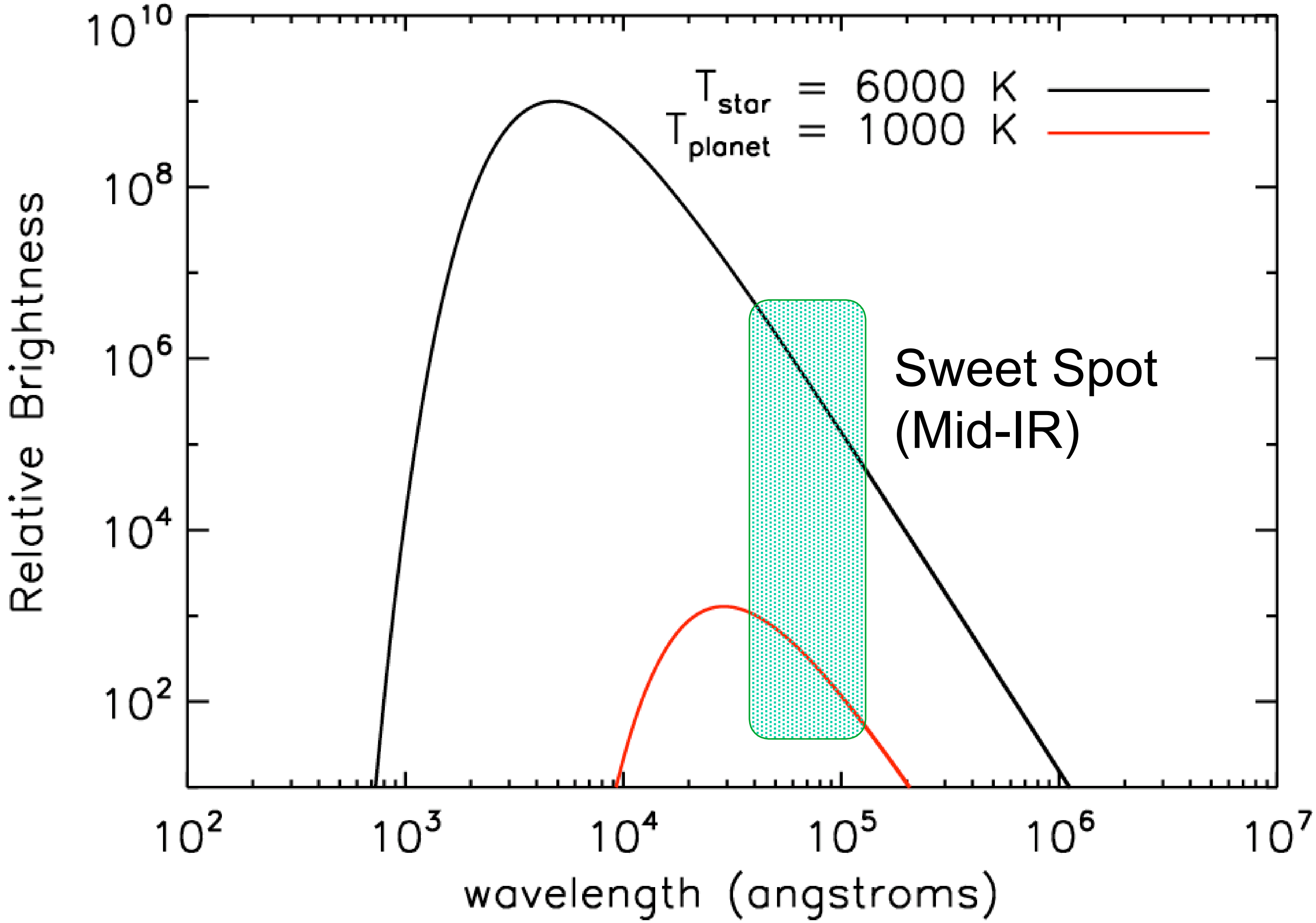
- Day-night temperature contrast ☑
- Atmospheric dynamics ☑

Secondary Eclipses

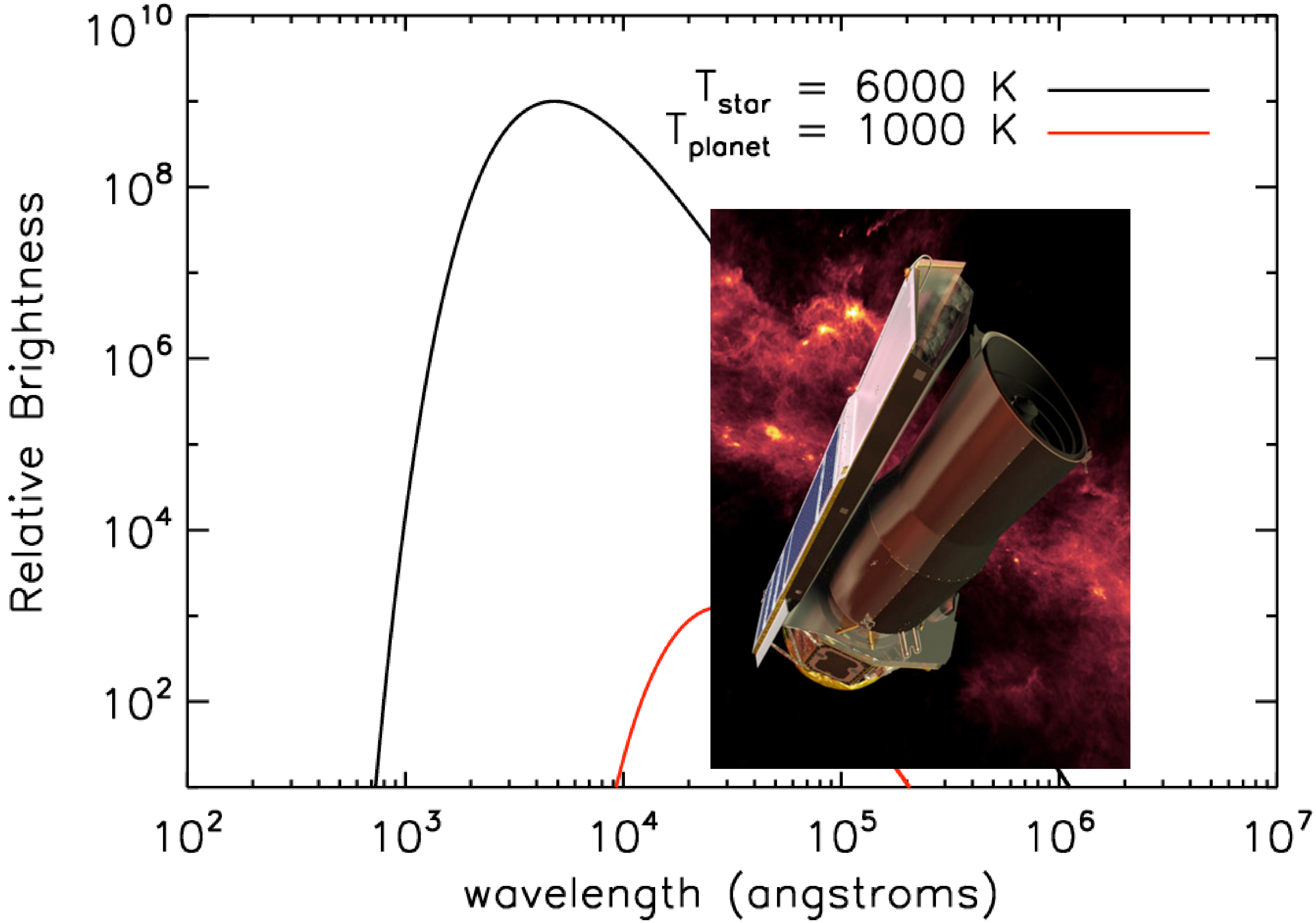
- Emission Spectrum (IR)
- Albedo (visible light)
- Eccentricity

slide due to H. Knutson

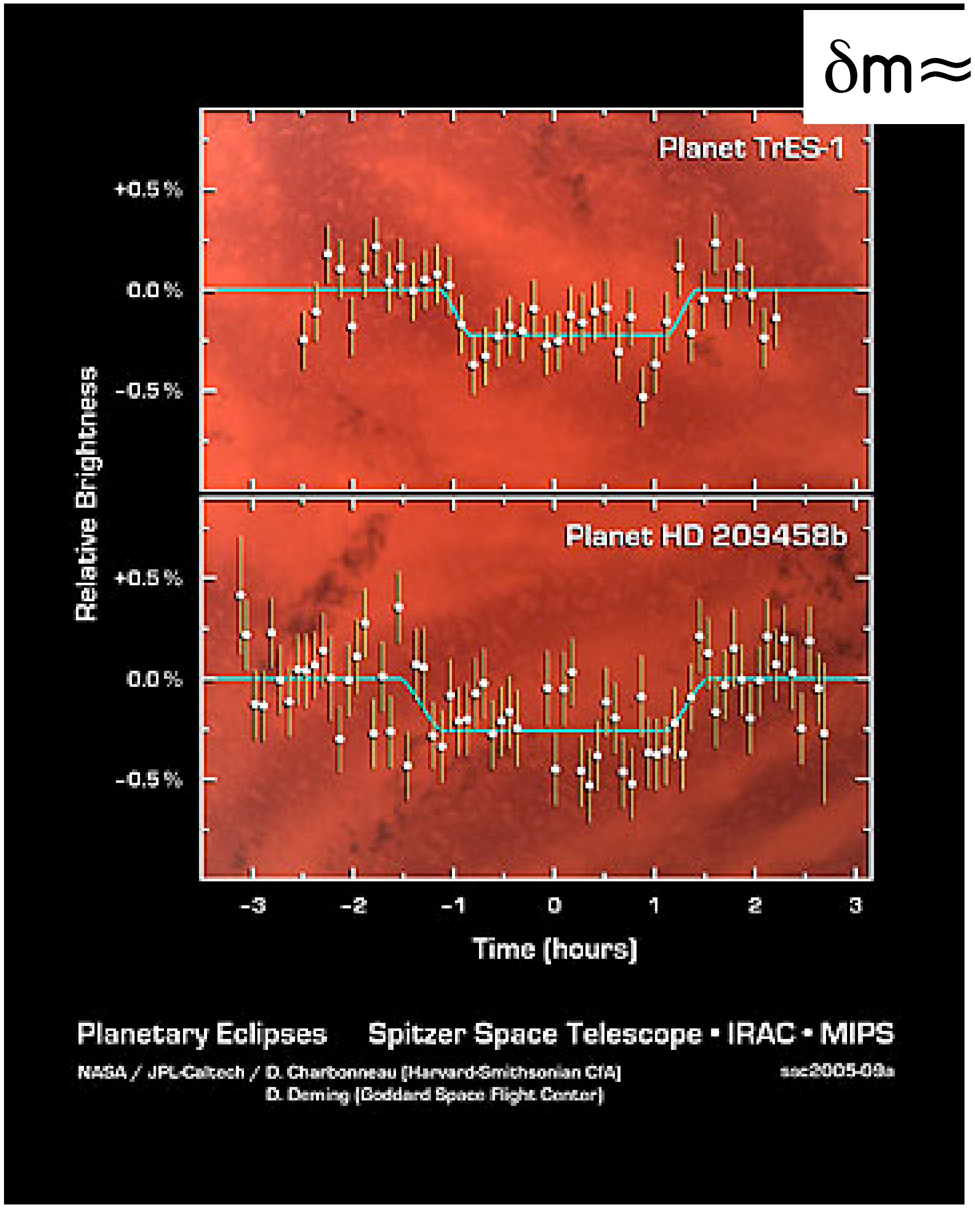
Thermal emission from hot Jupiters



Thermal emission from hot Jupiters



Spitzer Space Telescope - first direct detection of planets' light - 2005



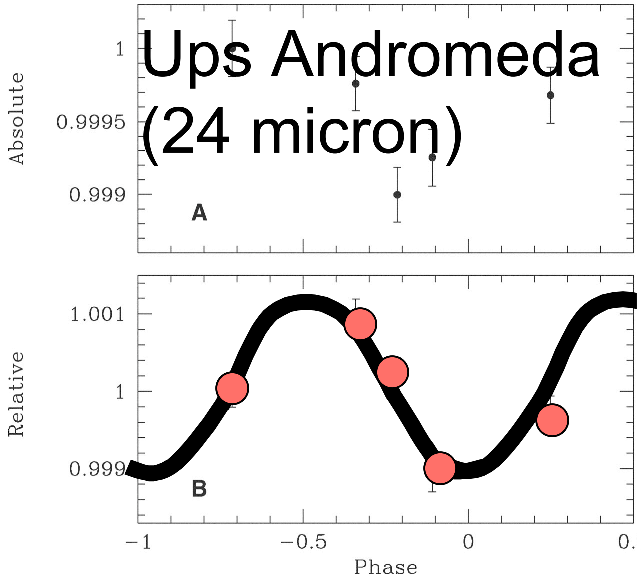
$$\delta m \approx (T_p/T_*)(R_p/R_*)^2 \approx 0.1\%$$

TrES-1: Charbonneau et al. (2005)

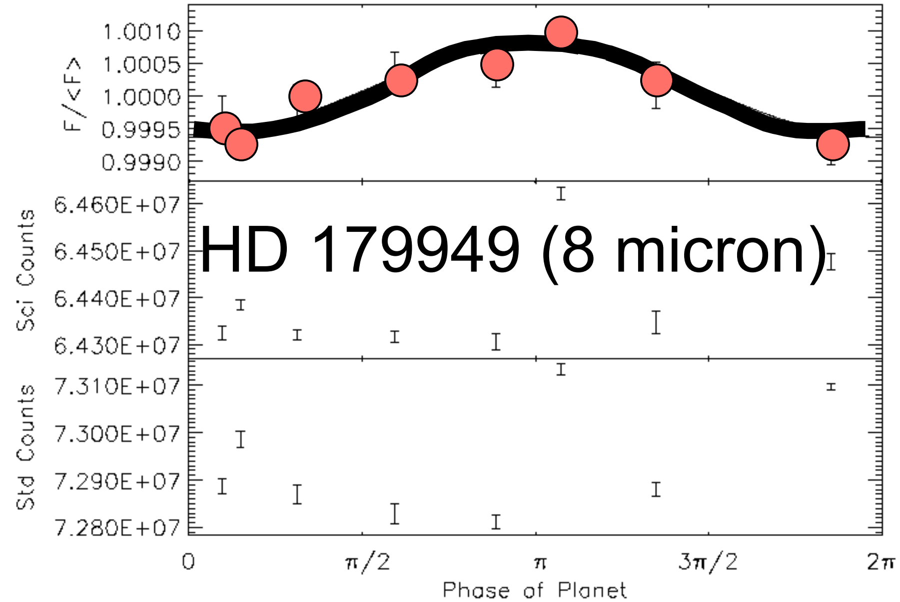
HD 209458b: Deming, Seager et al. (2005)

Gives temperature of day side - for *night*-side, need **phase function**

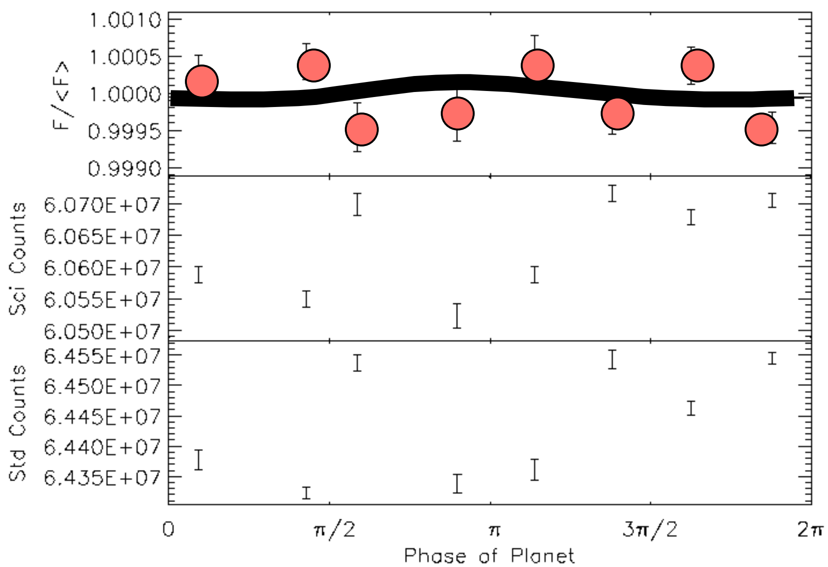
Phase Function: 1st Generation



Harrington, Hansen, Luszcz, Seager,et al. (2006)

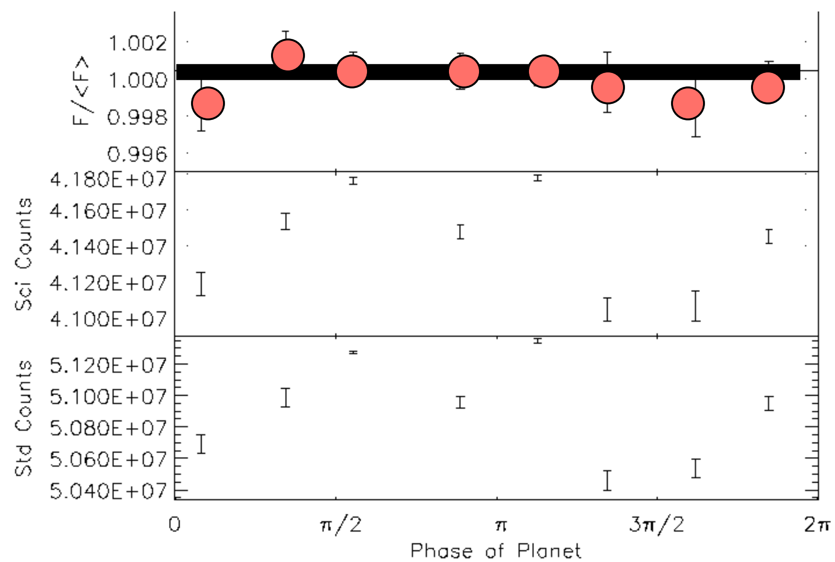


Cowan et al. (2007)



51 Peg (8 micron)

Cowan et al. (2007)

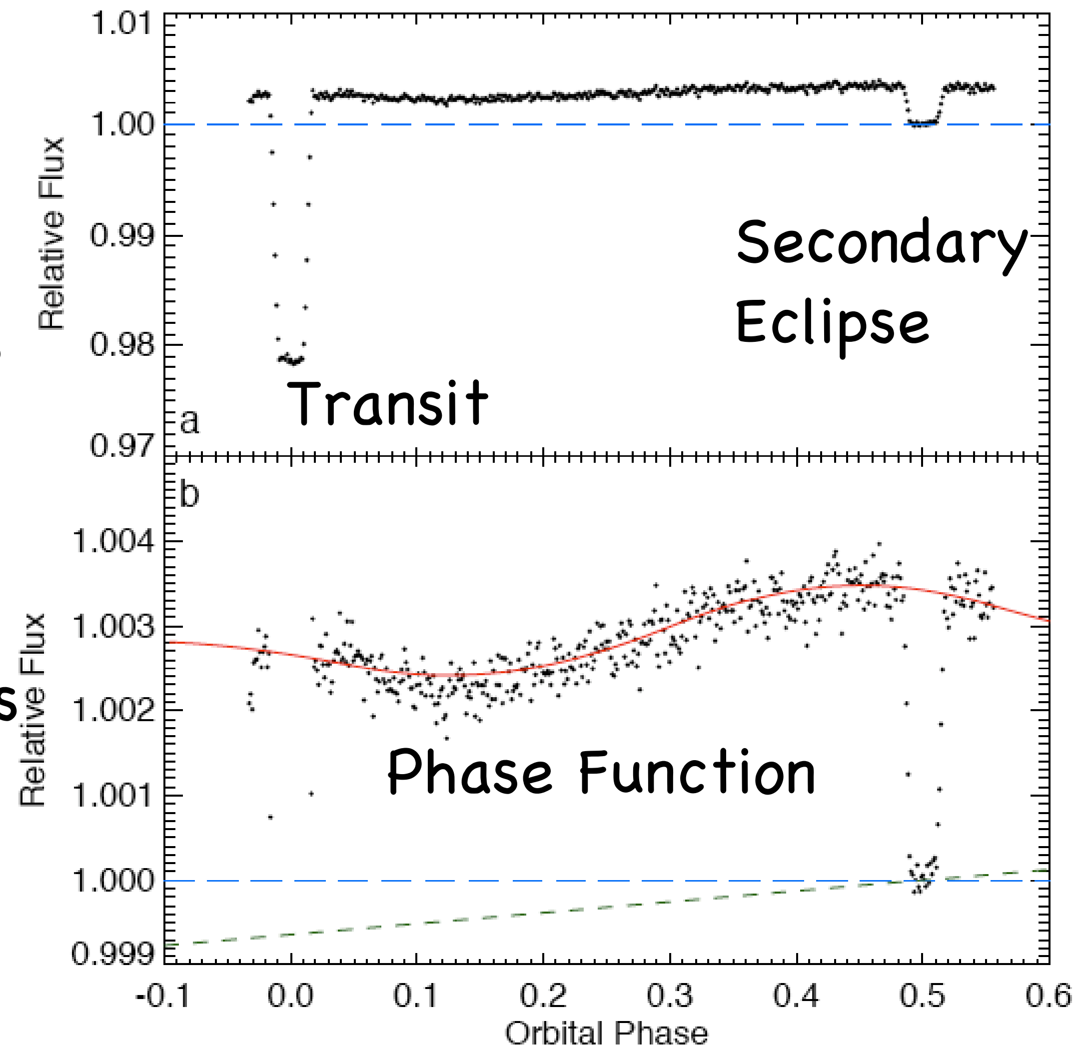


HD 209458 (8 micron)

Cowan et al. (2007)

HD 189733b Phase Variation

- Observed planet for ~1/2 orbit (33 hours, 0.25M exposures) at 8 μm using Spitzer/IRAC & 24 micron using MIPS
- Correct for detector ramp
- Small size of observed phase variation indicates relatively efficient circulation between day/night sides



Knutson et al. (2007,8)

Mapping a Hot Jupiter

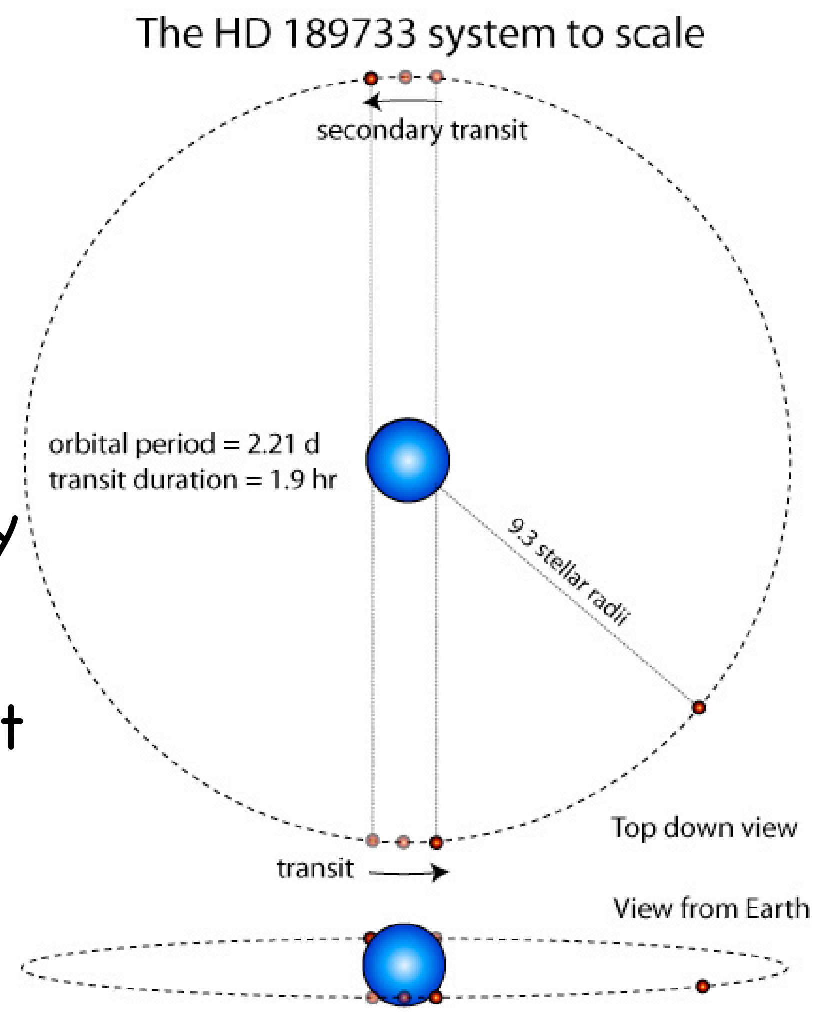
<u>Assumptions</u>:

- Planet surface brightness varies on a timescale longer than one orbital period in frame of rotation

- The planet is edge-on (very nearly)

- No limb darkening of planet

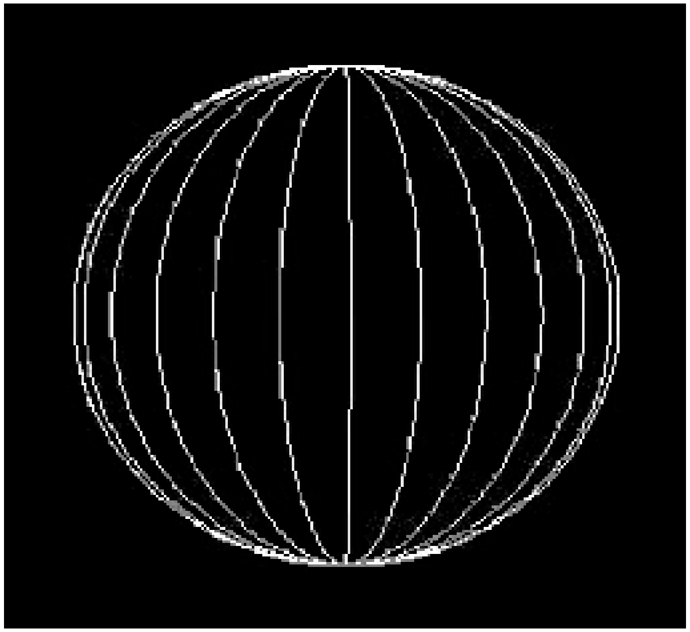
- Neglect or correct for stellar variability



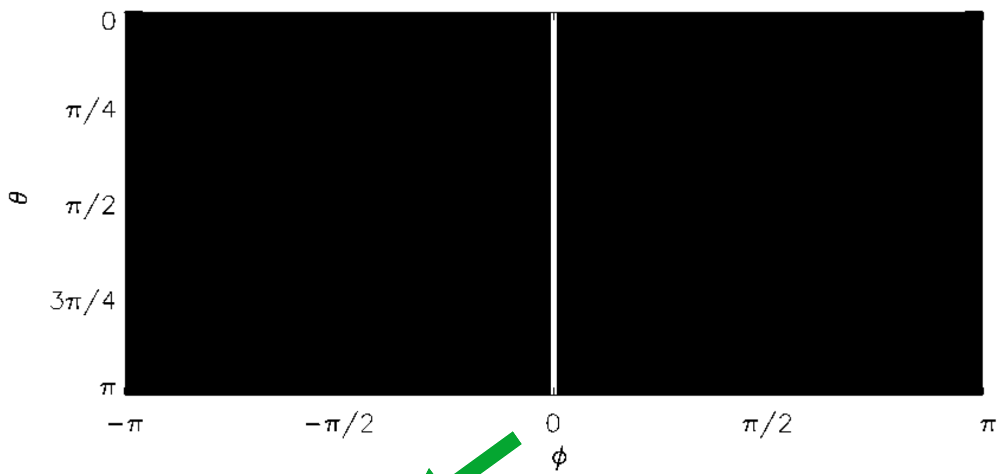
Mapping a Hot Jupiter

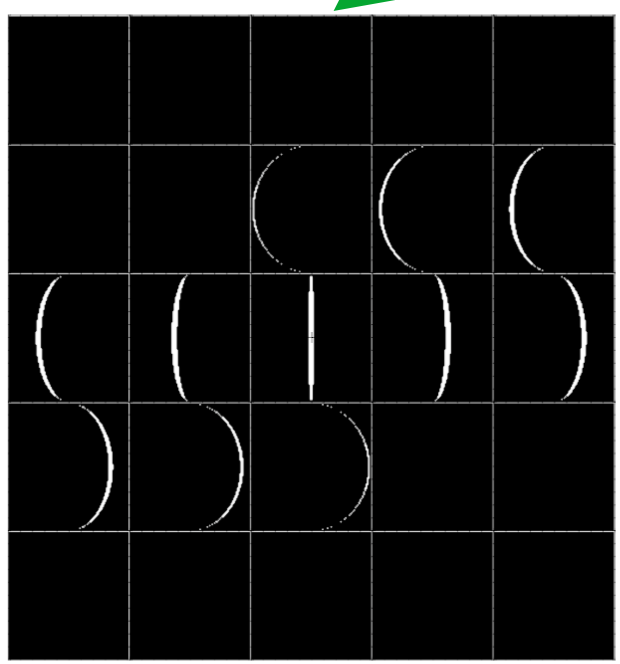
Inversion:

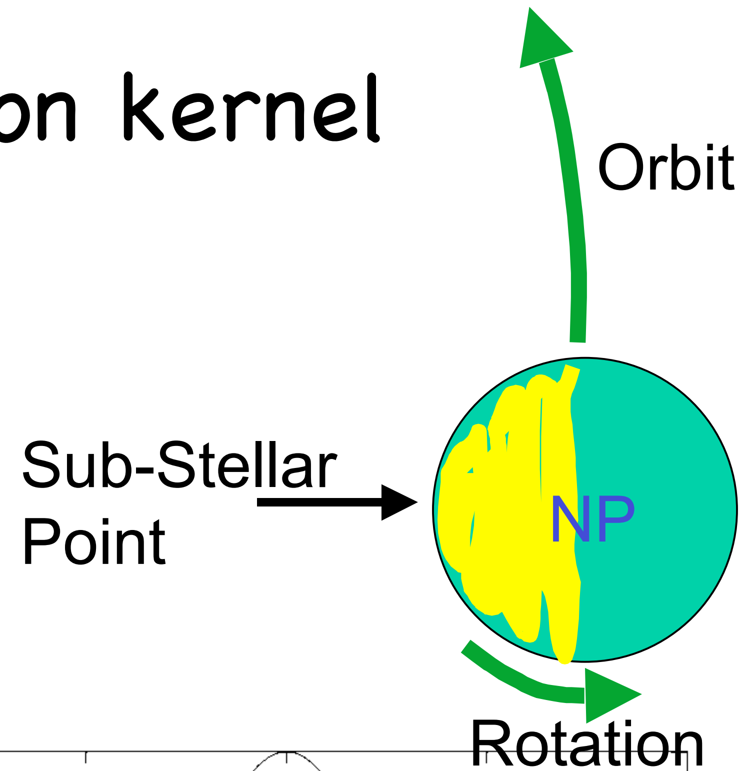
- Divide the planet into longitudinal slices or longitudinal Fourier modes
- At each point in time, all (or part) of about half of the slices are visible
- As the planet rotates, each on the terminus rotates into or out of view

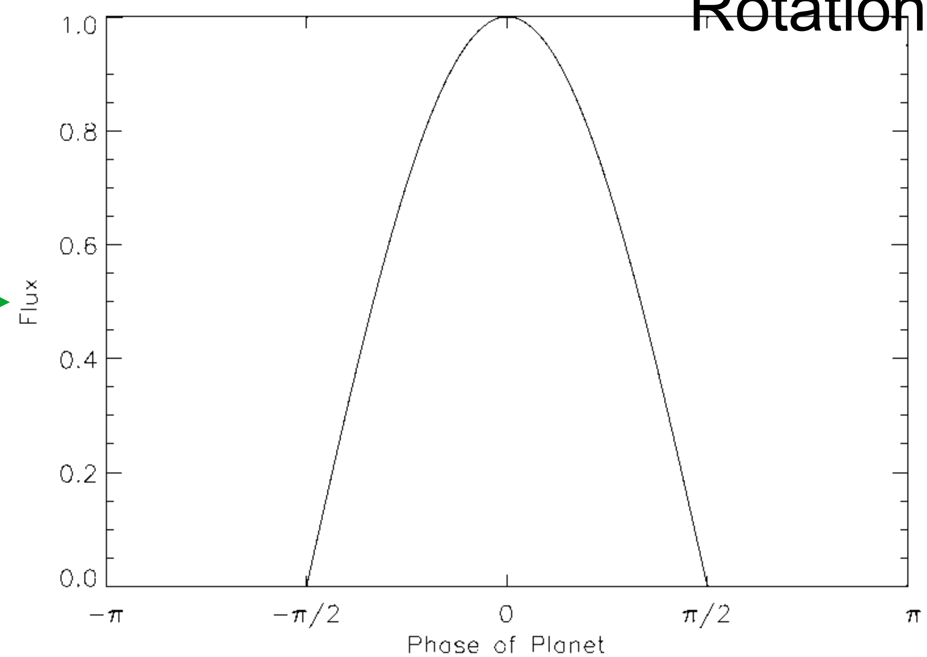


Phase function kernel

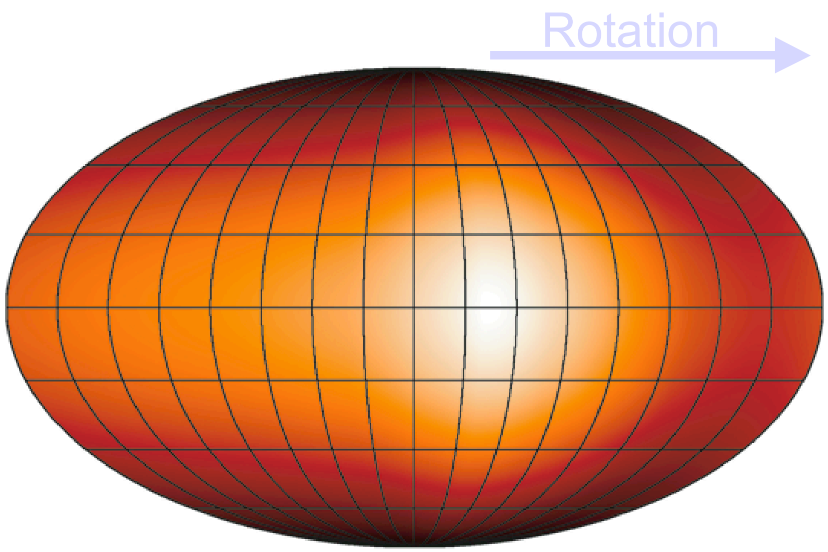


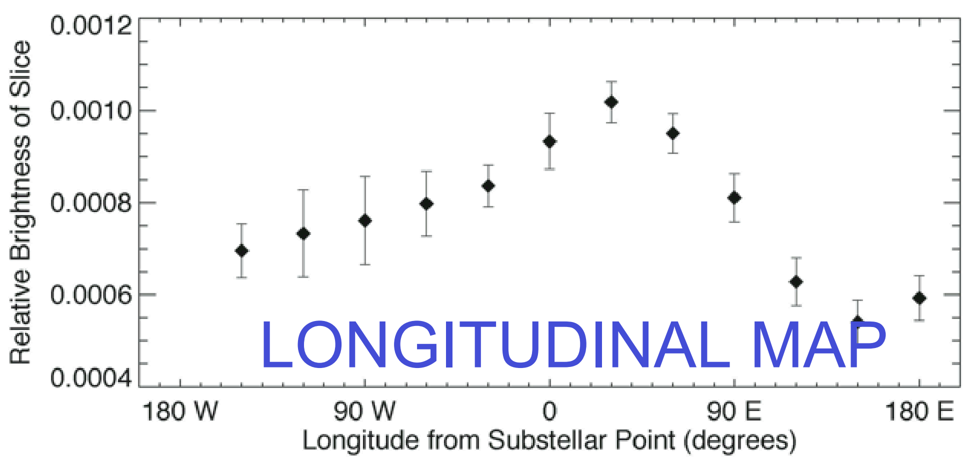






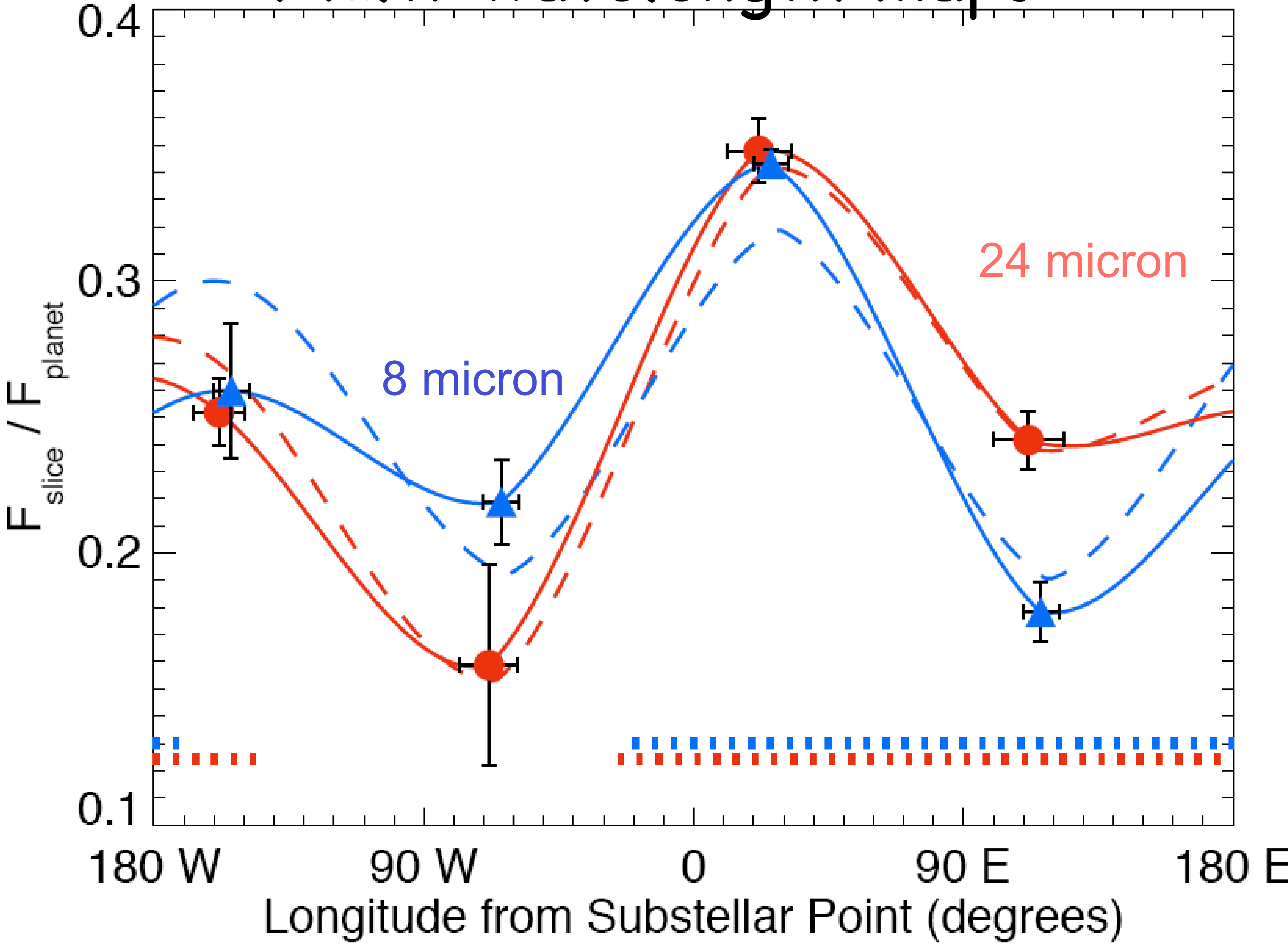
Longitudinal map of a hot Jupiter





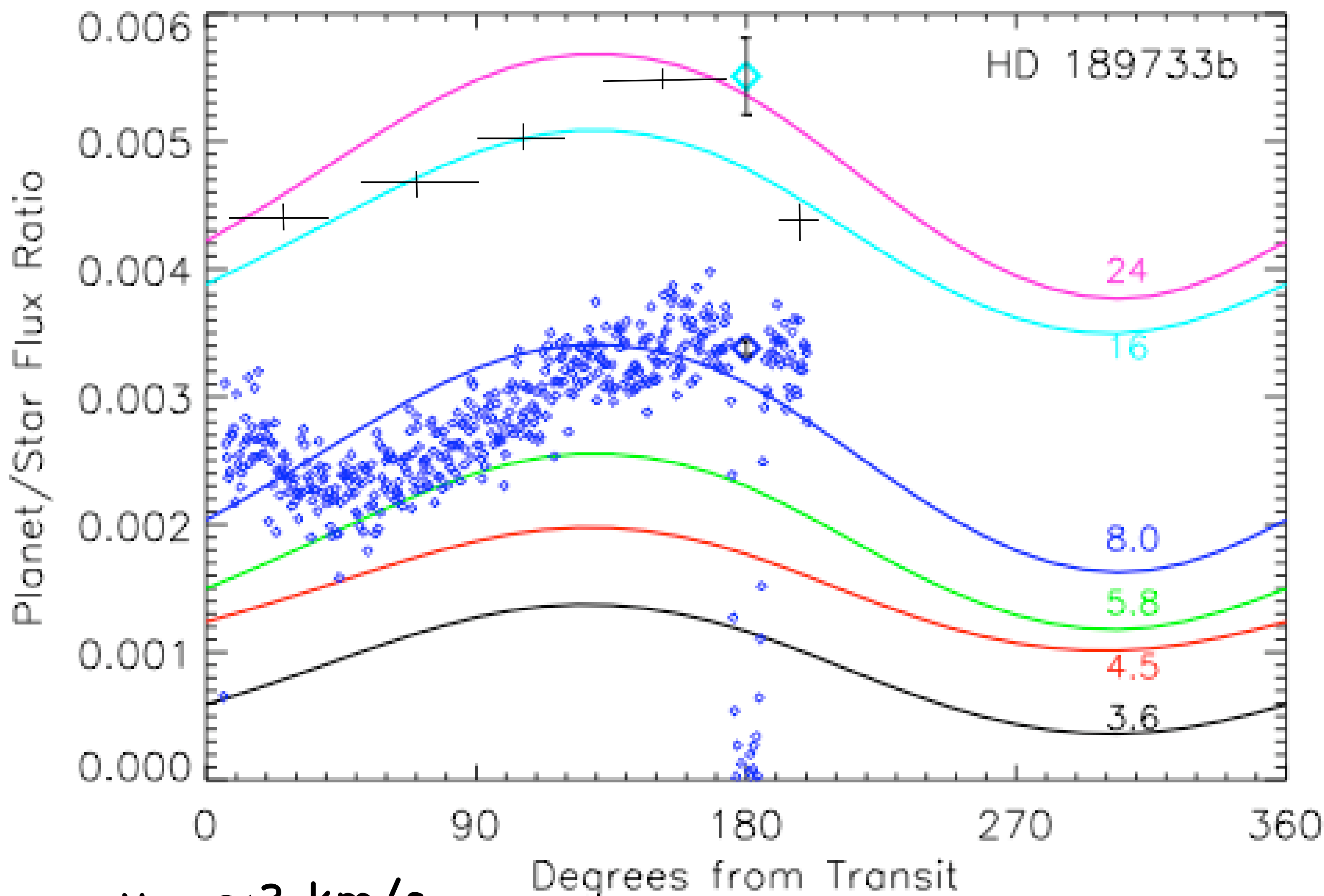
- Regularized inversion gives face-on flux of 12 longitudinal "slices"
- Hot spot is ~30±10 degrees away from substellar point (~25 mbar level) - agrees with Fortney et al. (2006) prediction: at photosphere $\tau_{rad} \approx \tau_{advect} \approx$ 6 hours
- $T_{b,max}$= 1200 K, $T_{b,min}$= 973 K

Multi-wavelength maps



Knutson et al. (2008)

Dynamics + radiation model



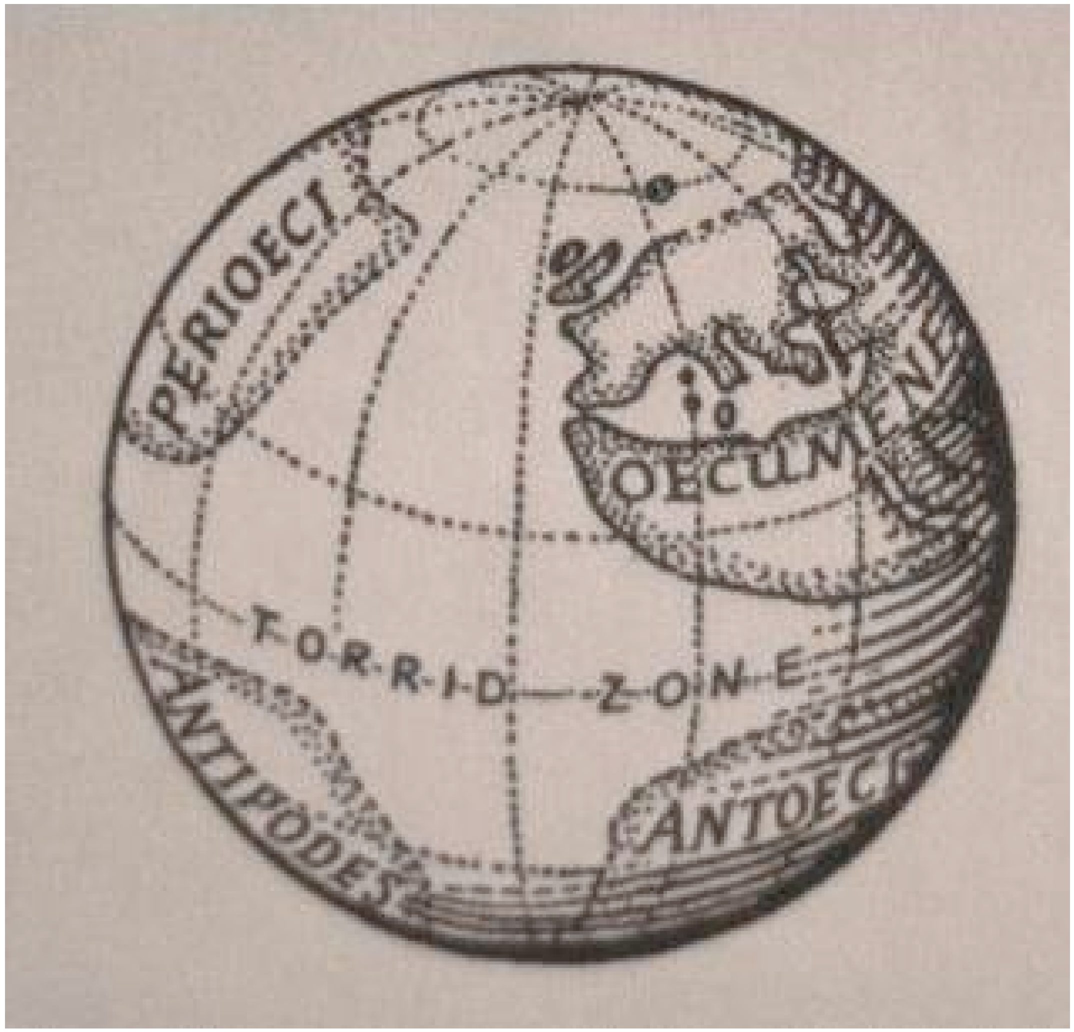
$v_{max} \approx 3$ km/s

Showman et al. (in prep.)

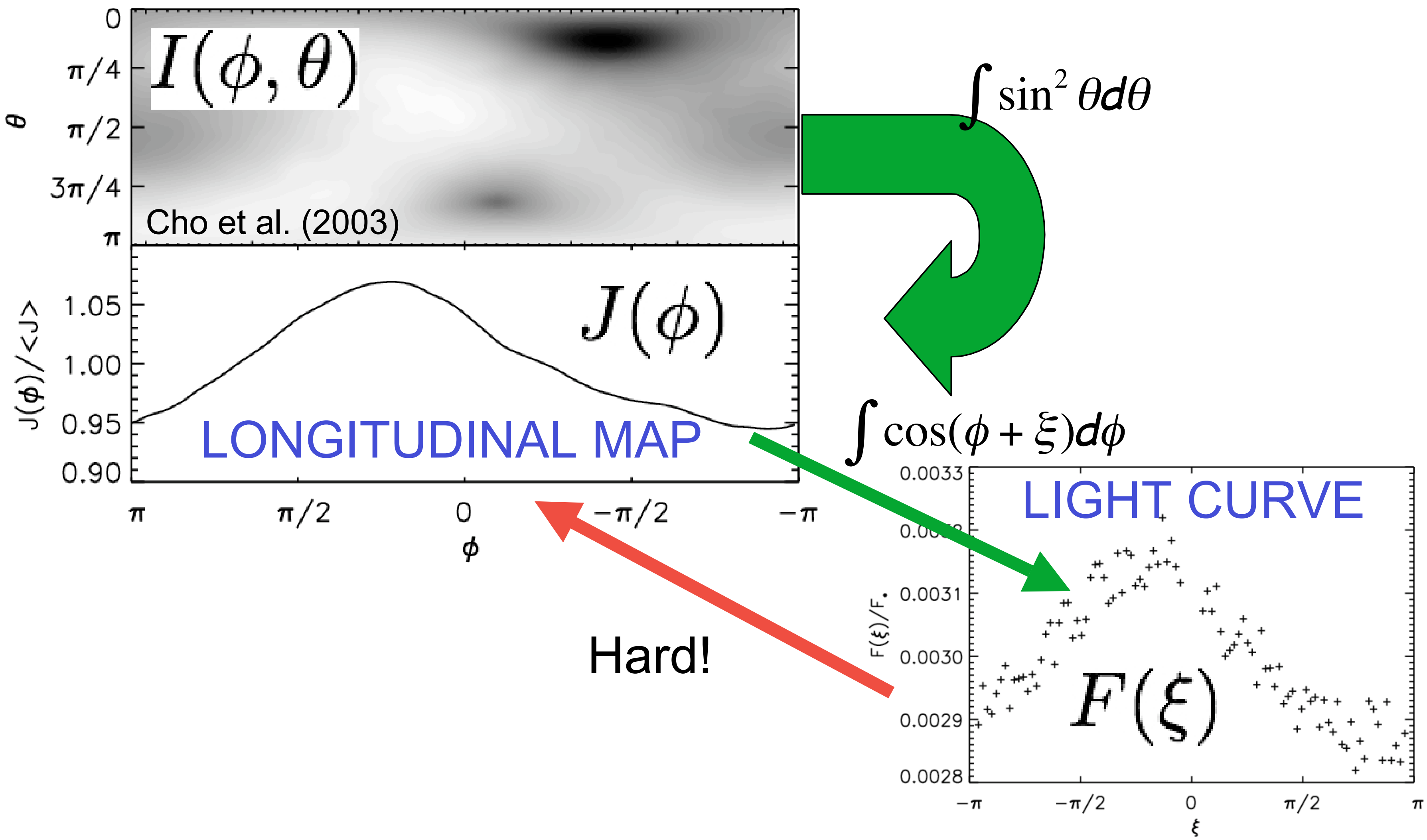
Implications

- Small day-night contrast: effective circulation at depth of photosphere
- Equatorial super-rotating jet is plausible explanation ~few km/s
- Radiative timescale is comparable to advection timescale at 8 & 24 μm photosphere - offset hot spot
- Yarkovsky effect may cause evolution of semi-major axis by ~few % (Fabrycky 2008)

Crates' Globe circa 150 BC

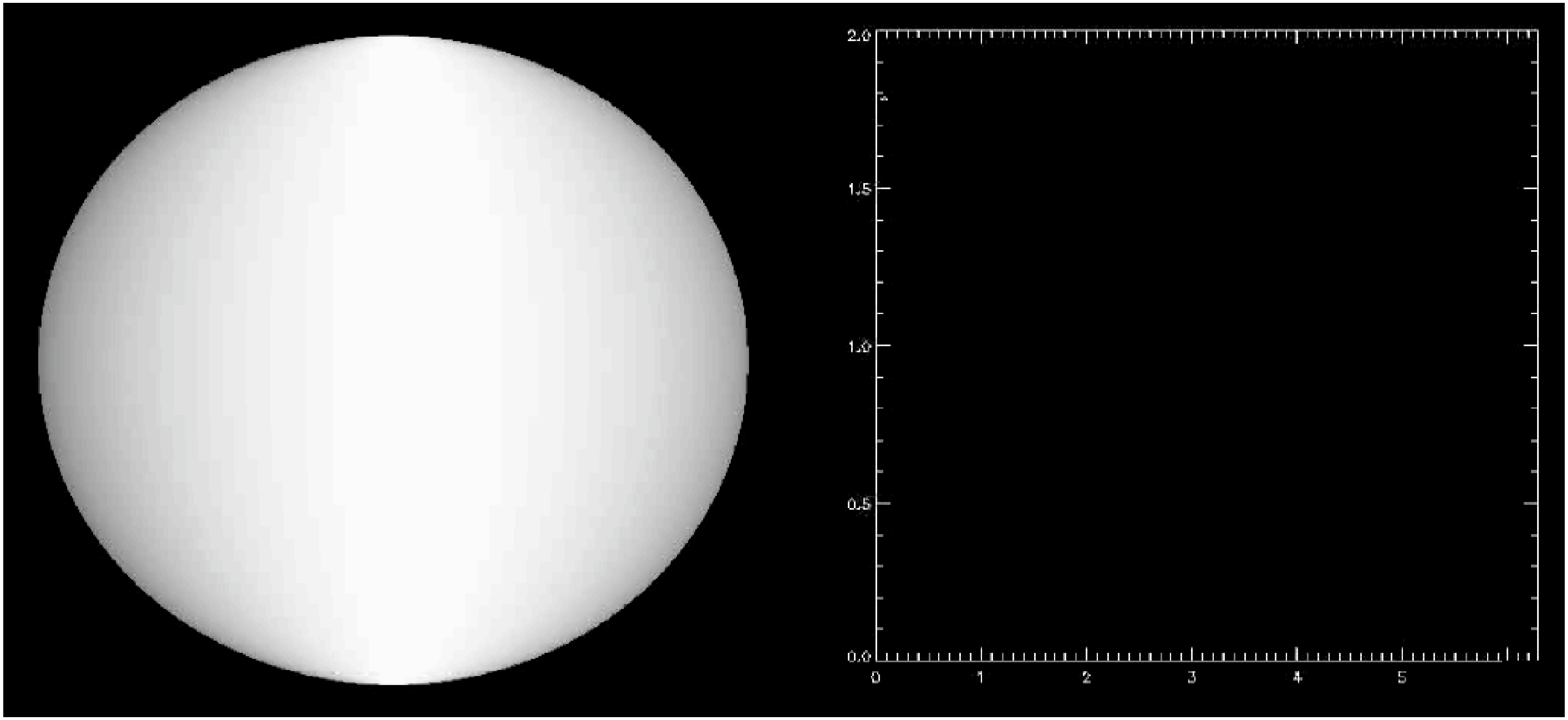


Planet map w/ full lightcurve



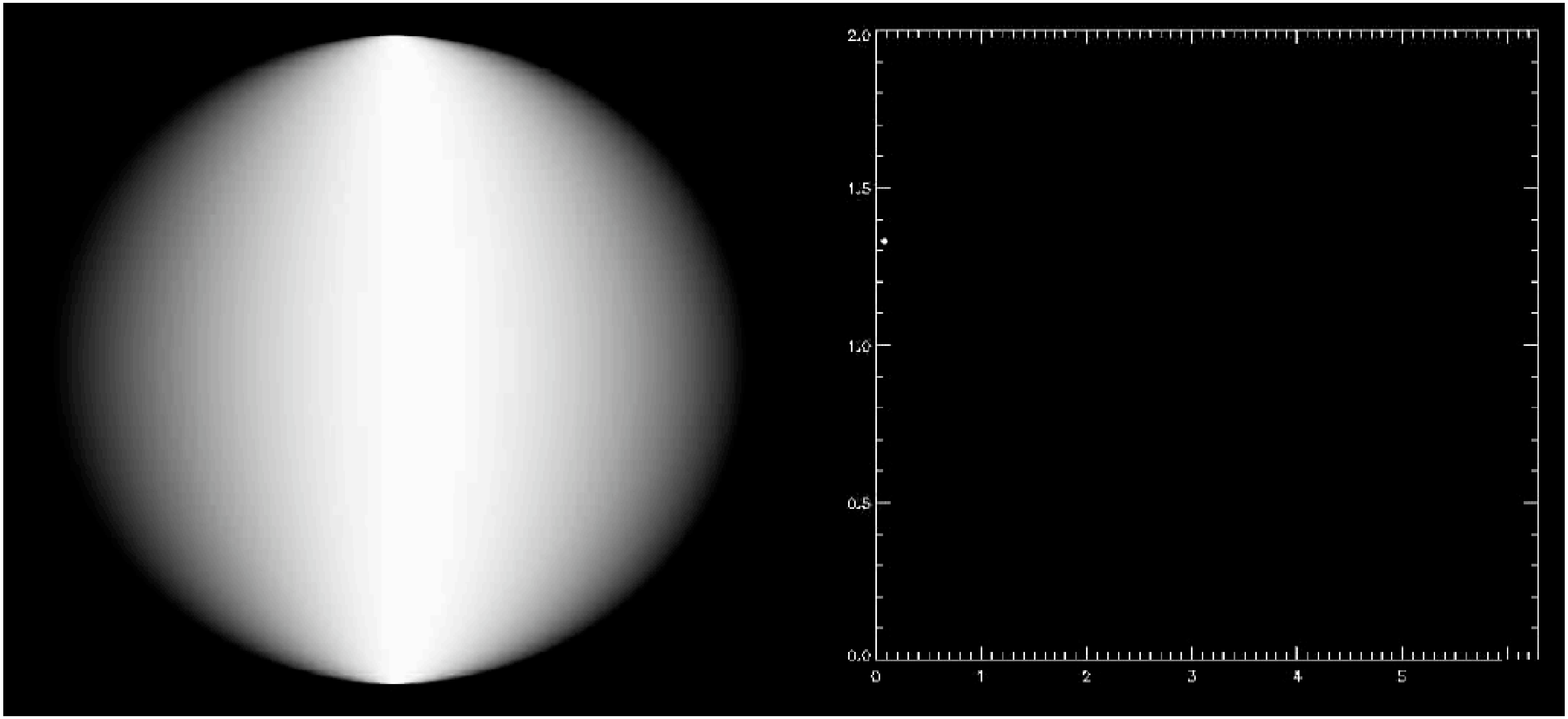
Fourier decomposition

$\cos(\phi-\phi_0)$

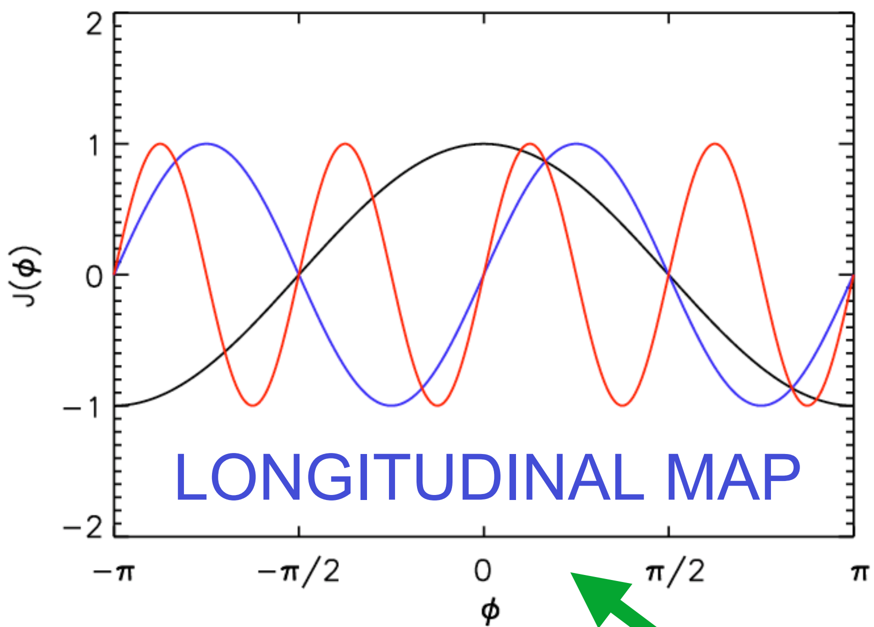


Fourier decomposition

$\cos(2(\phi-\phi_0))$

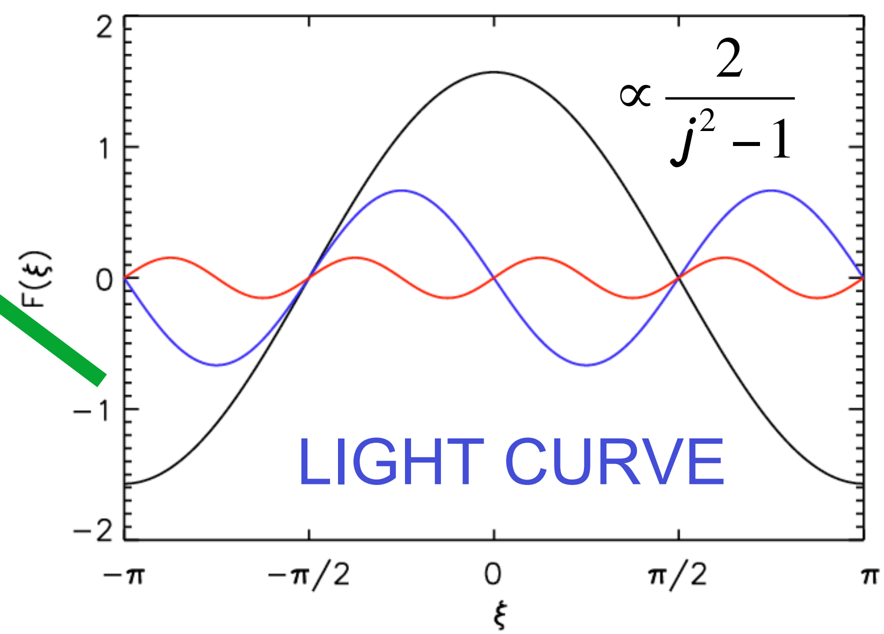


Sinusoidal Maps



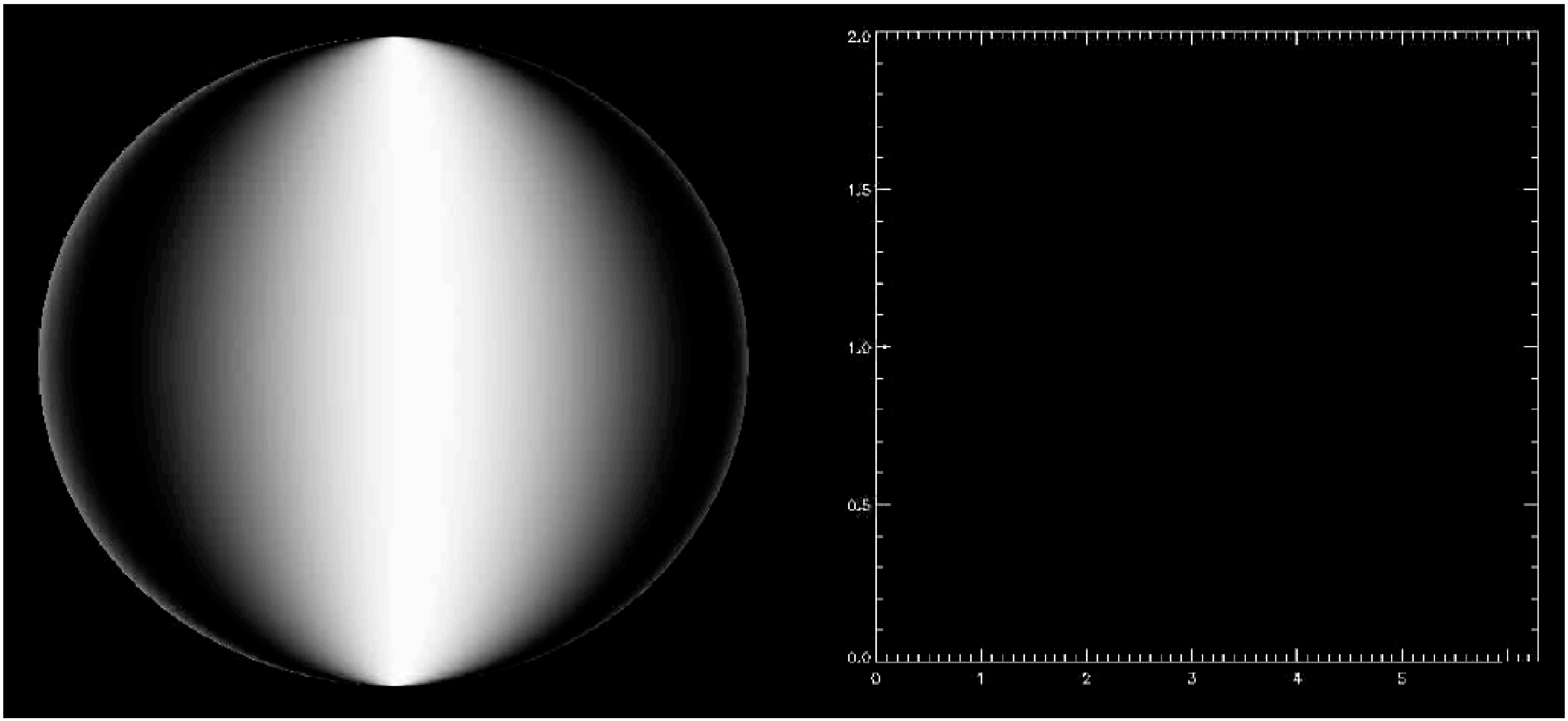
Higher Frequencies get damped out

Easy for j=1 and even modes (j=2,4,…)

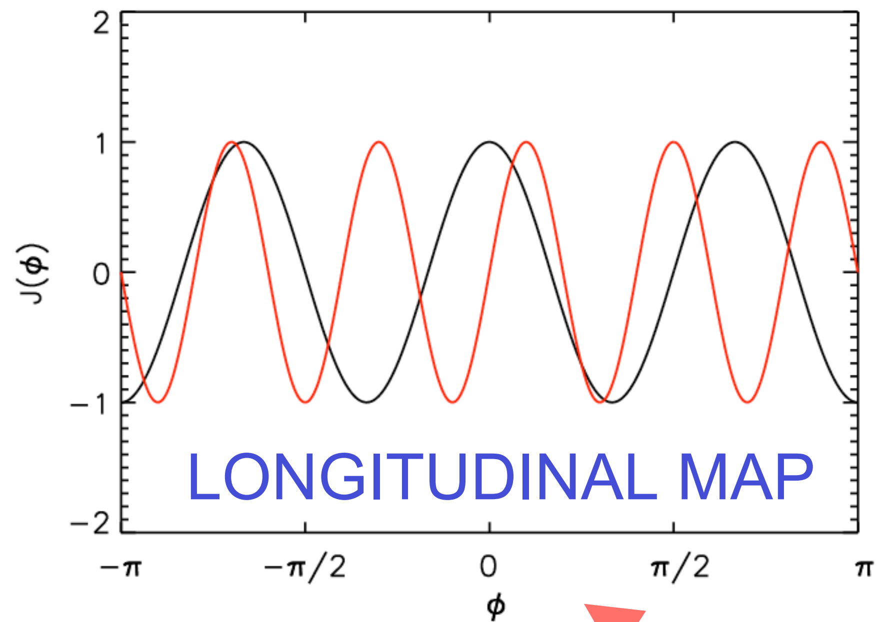


Fourier decomposition

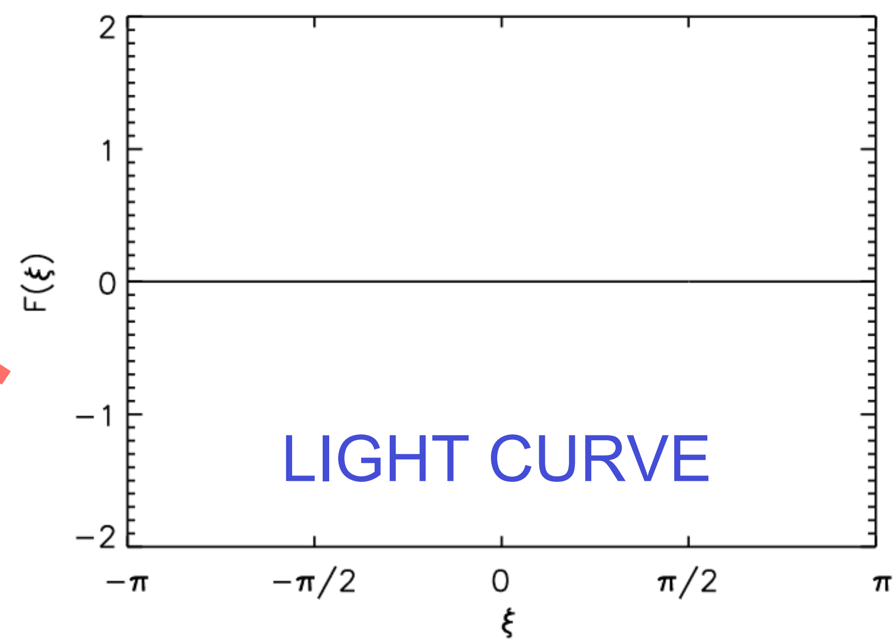
$\cos(3(\phi-\phi_0))$



The Problem of the Odd Modes



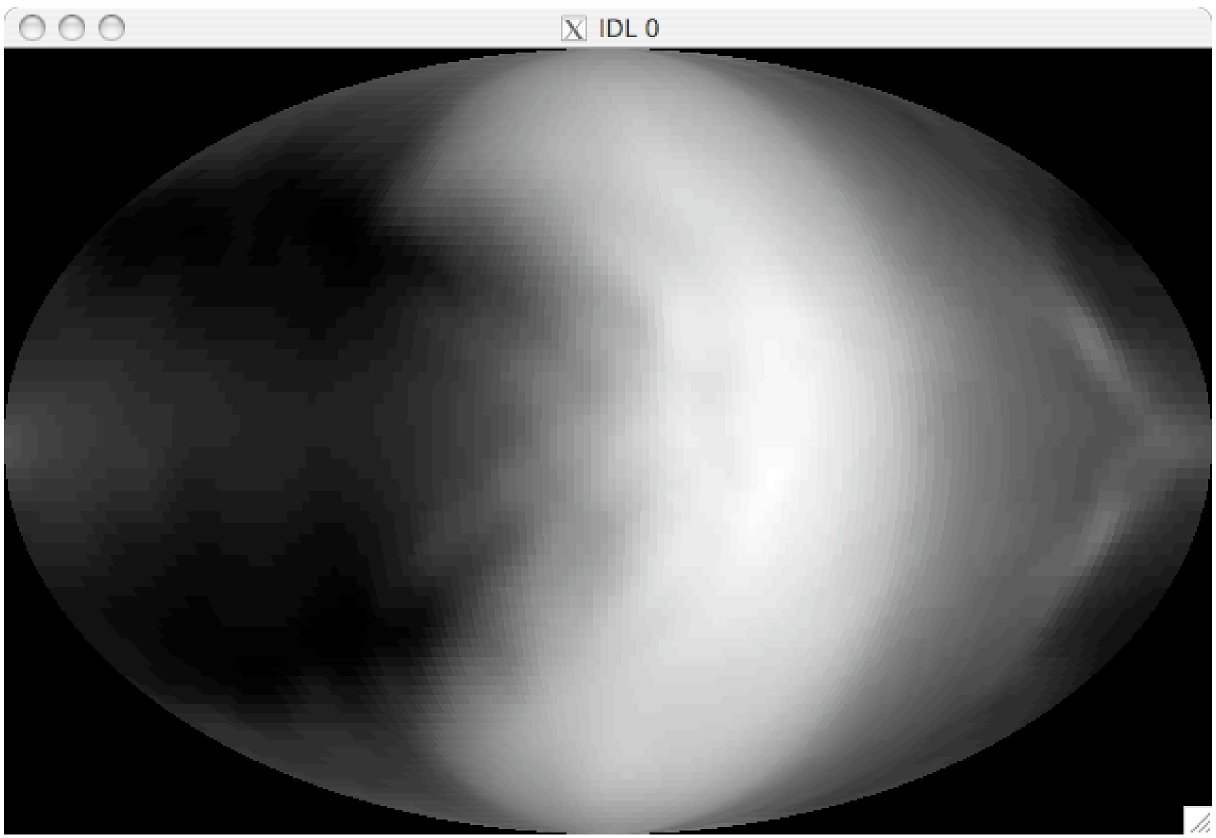
Odd modes (other than j=1) cancel out by symmetry



No way to recover missing information!

Noise-free Planet Mapping

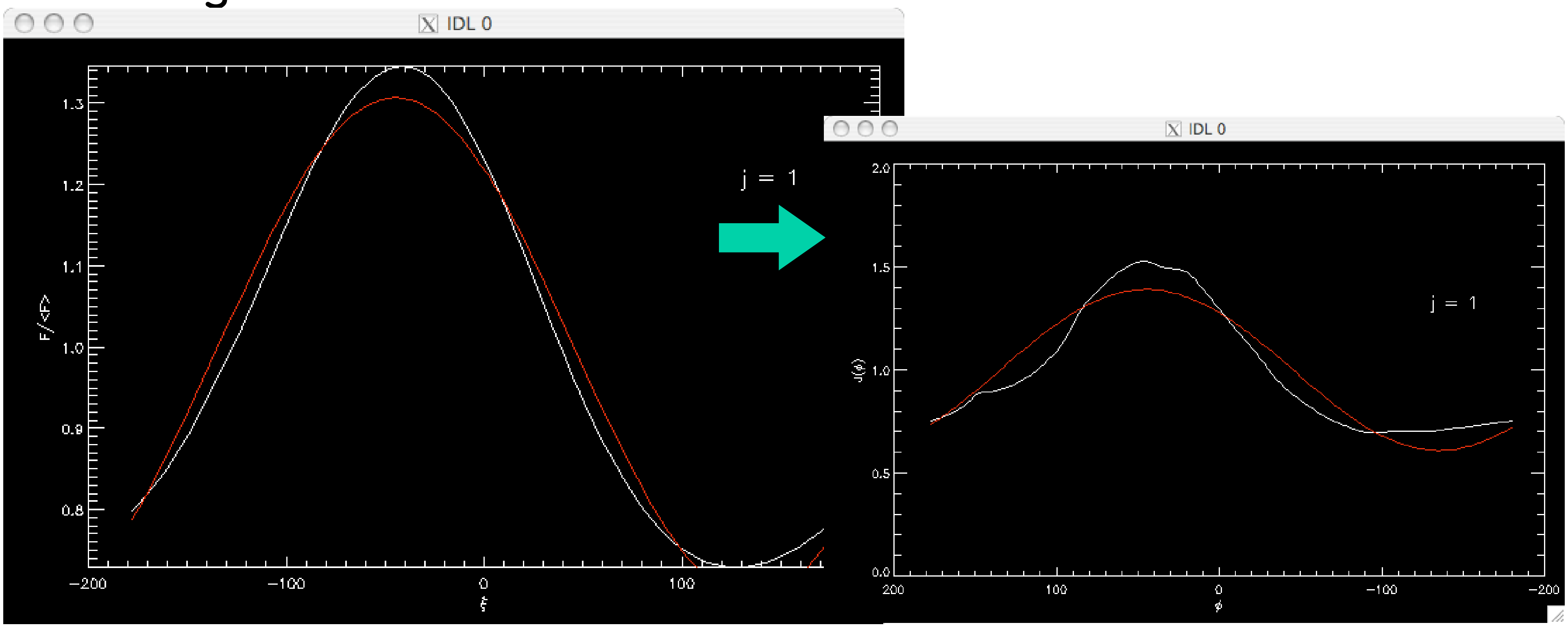
- Temperature at depth of 100 mbar from 3D global climate model of HD 189733 (Showman et al. 2008) - 8 micron flux assumes blackbody:



Cowan & Agol (2008)

Noise-free Planet Mapping

- Phase function can be fit with sinusoids from 0 to j.
- Coefficients can be converted back to planet longitudinal flux:



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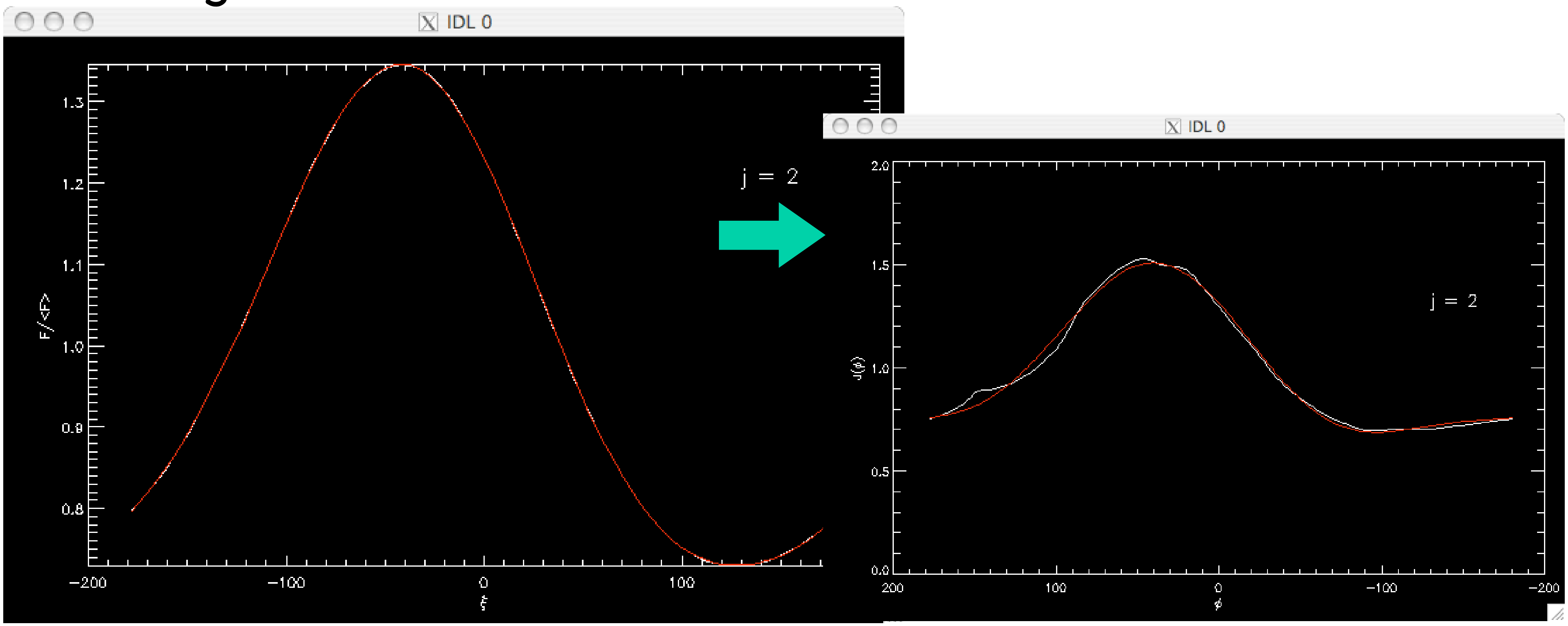

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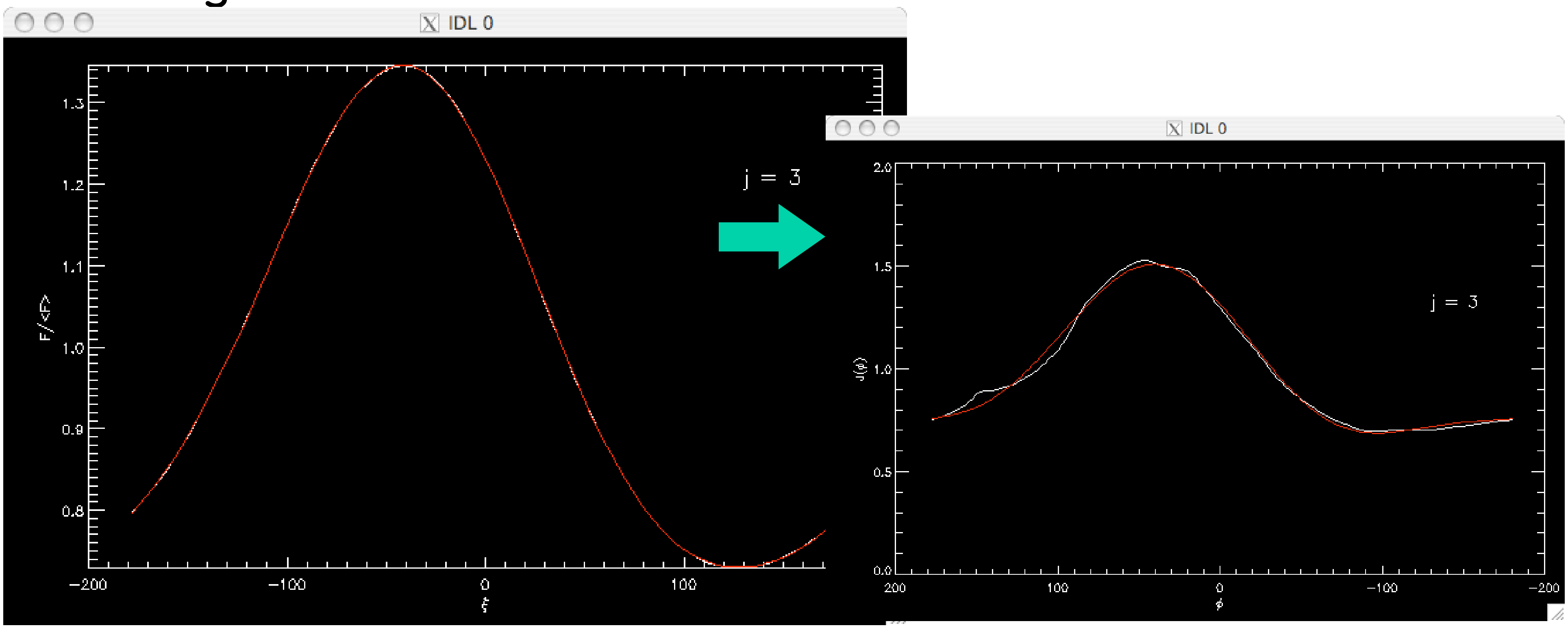
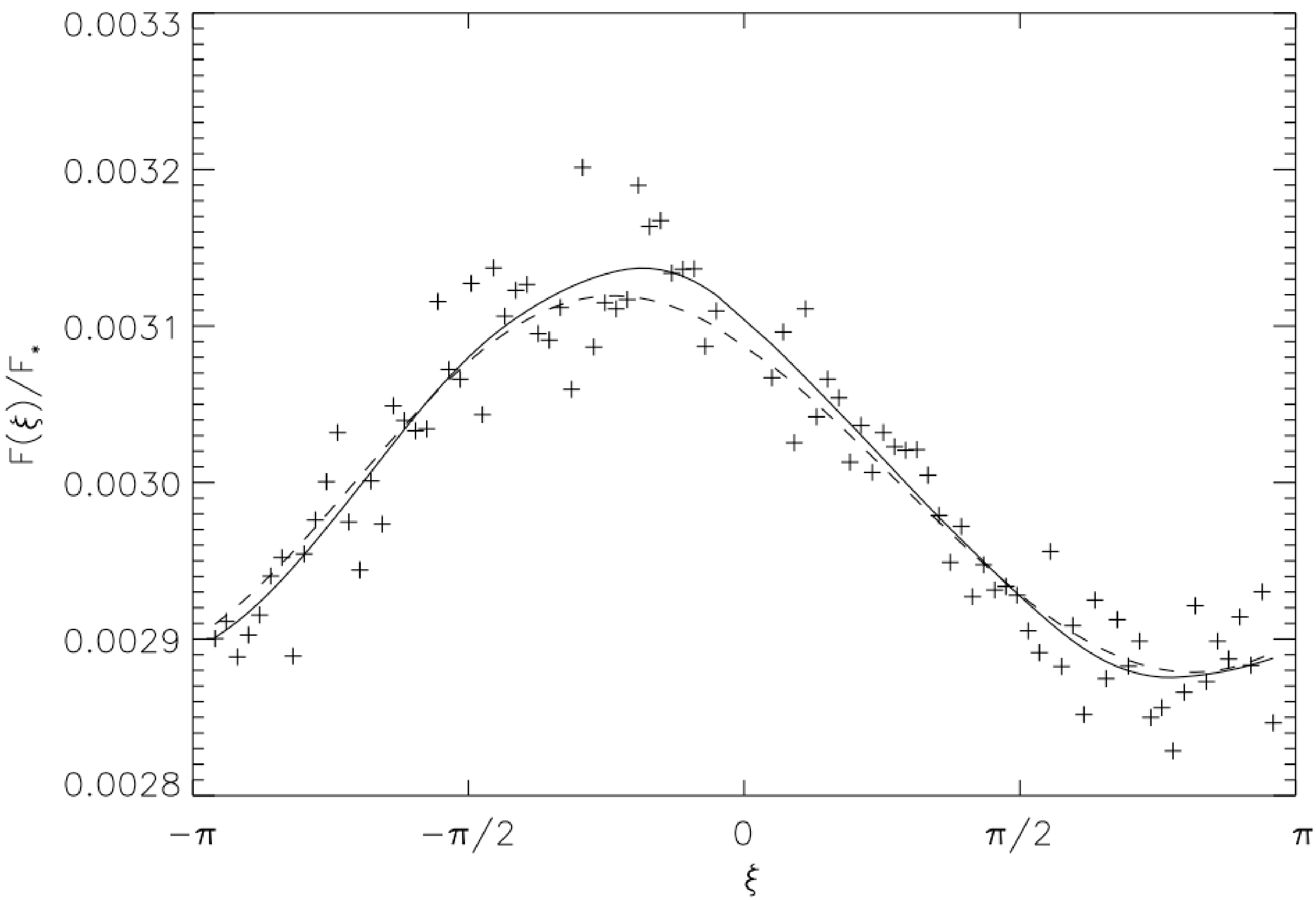
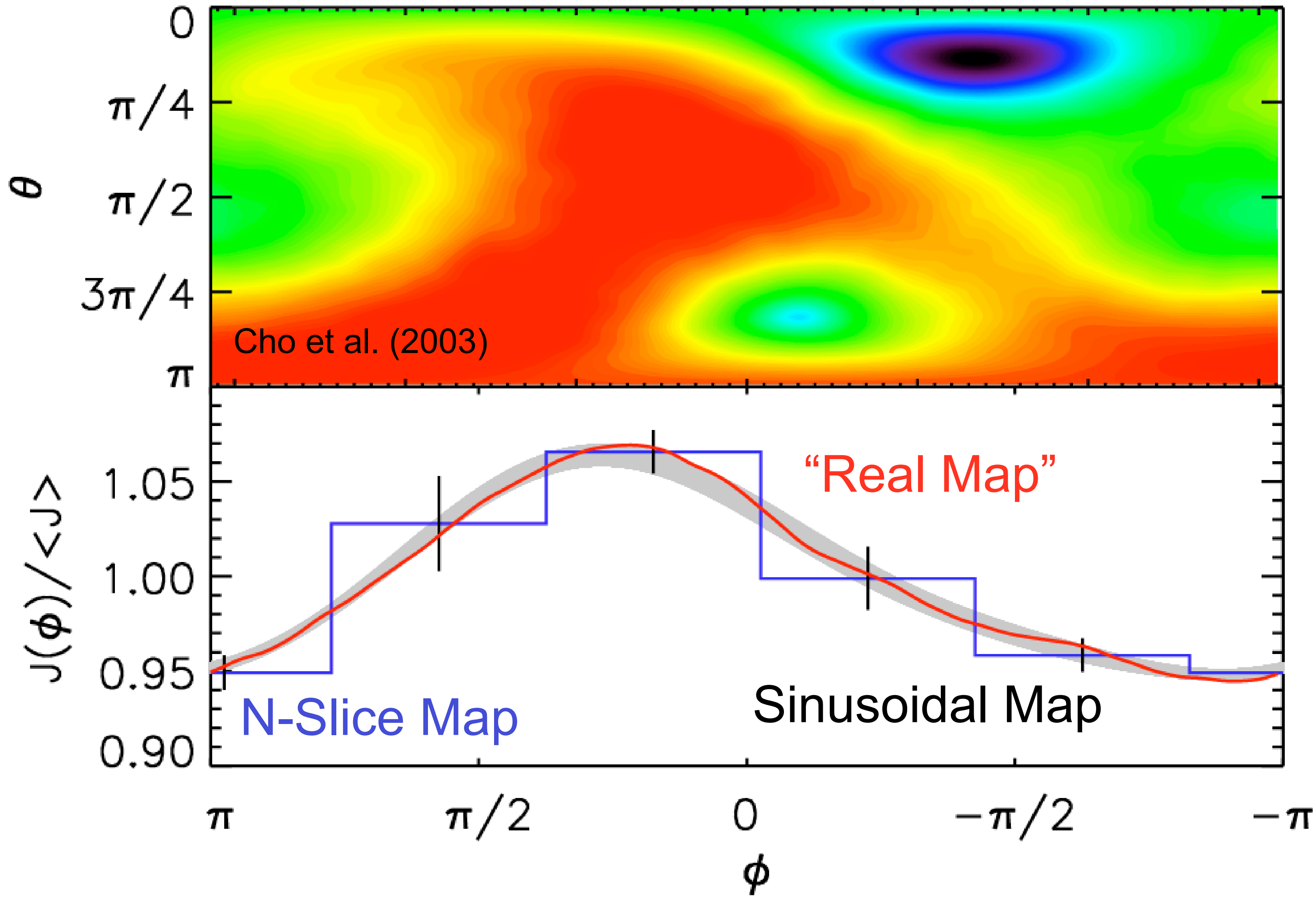


Typical amplitude of j=3 modes is 1-10% of j=1 mode.

Planet mapping with noise

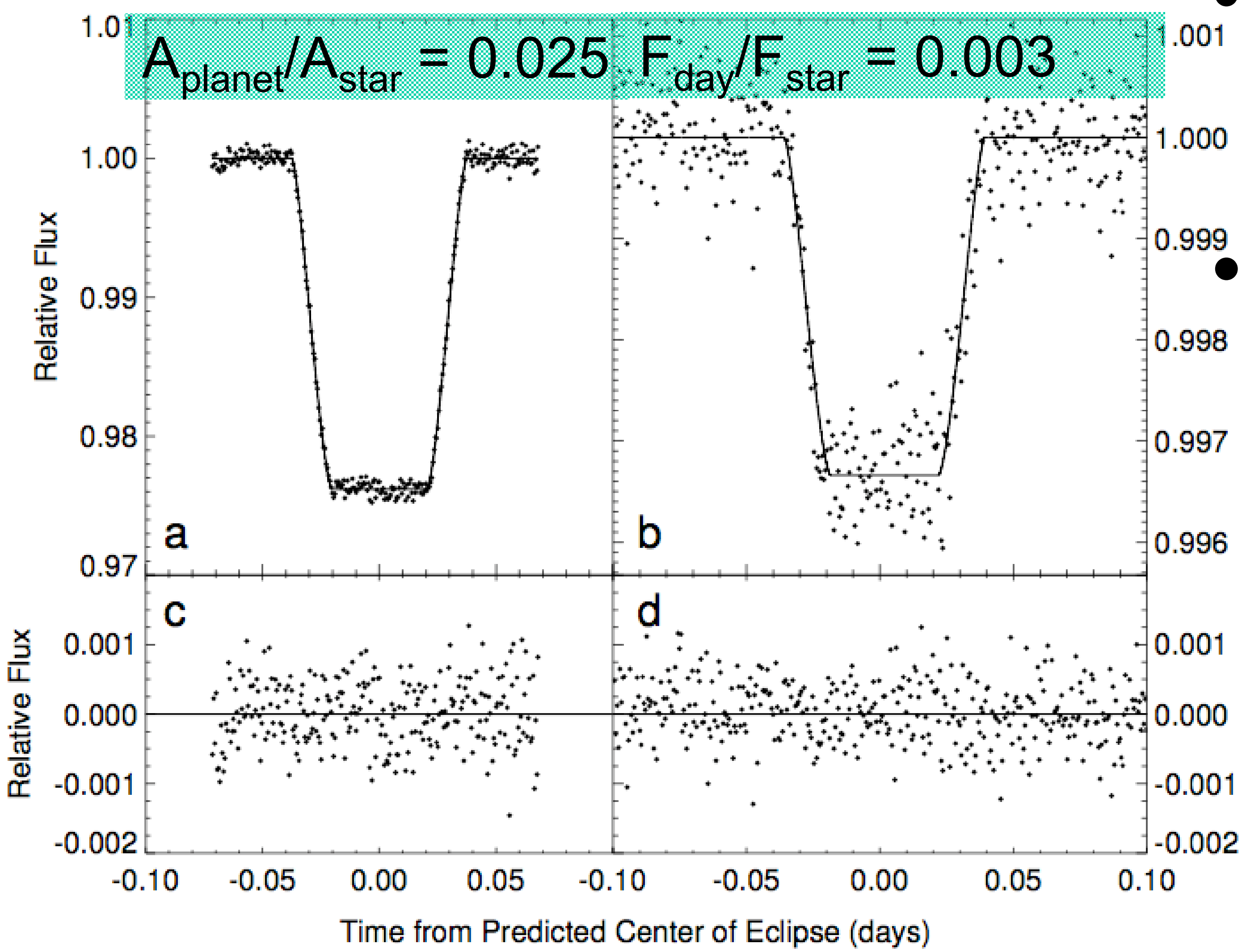


Planet mapping with noise



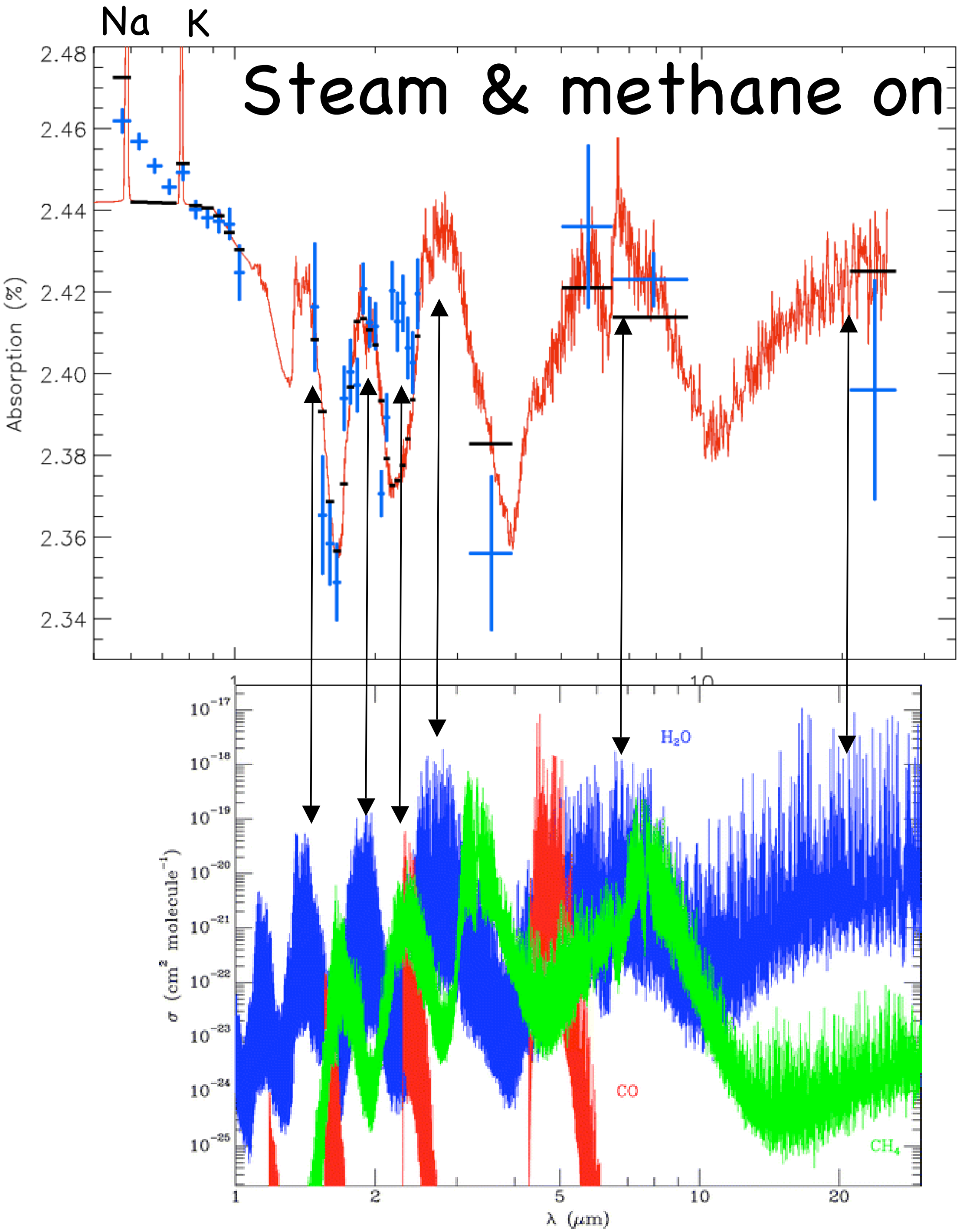
Cowan & Agol (2008)

Transit & Secondary Eclipse



- Most precise transit time ever! (6 s uncertainty)
- 2nd eclipse occurs 120±24 s late after accounting for 30 sec light travel time (eccentric orbit? $e \cos \omega \approx 0.001 \pm 0.0002$)

Steam & methane on HD 189733b



Model: Tinetti et al. (2007);

Data: Beaulieu et al. (2007), Knutson et al. (2007,2008), Pont et al. (2008), Swain et al. (2008)

Fortney et al. (2006)

Infrared phase function summary

- Hot spot is offset eastward - superrotating jet &
- Longitudinal mapping of planet is limited by j=3 frequency (invisible); j=4 is suppressed (too small for JWST), so can be fit with 5 parameters

$$F(\xi) = F_0 + F_1 \cos(\xi - \xi_1) + F_2 \cos(2[\xi - \xi_2])$$

Global Average Temperature

Big Equatorial Hot/Cold Spots

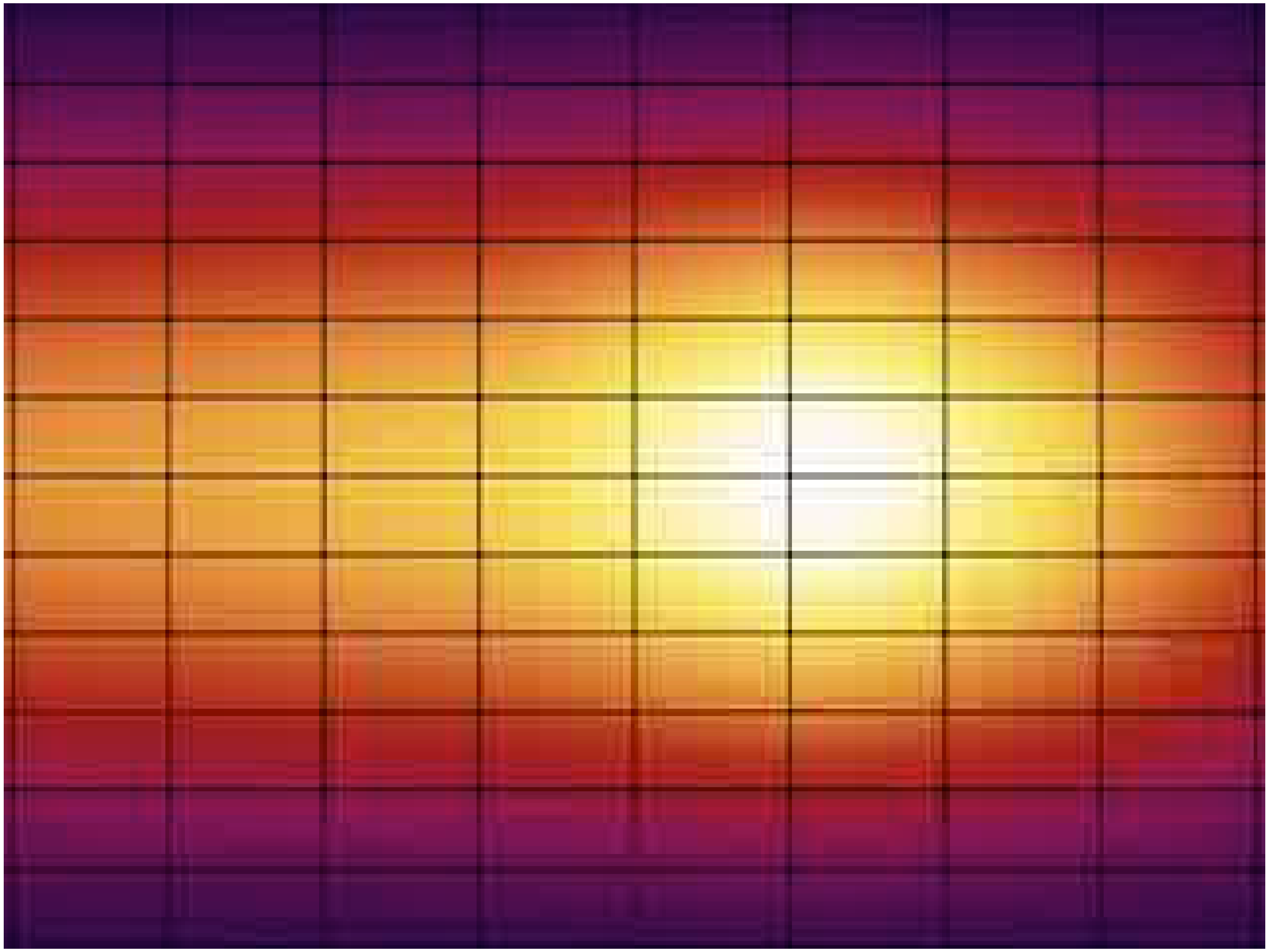
Small Equatorial Hot/Cold Spots

- Day/night contrast indicates advection of energy to night side is efficient at depth of mid-IR photosphere (amplitude & offset consistent with latest models)
- Wavelength dependence of transit depths can be fit with H_2O, CH_4 & Rayleigh scattering

Other Spitzer Programs

- KH 15D - IRAC, eclipsing binary T Tauri Star
- Gravitational microlensing of a quasar (next week)
- Hot Jupiter phase functions - Knutson et al. 2007; Cowan et al. 2007; Cowan & Agol 2008 Agol 2008; Knutson et al. 2008 (in press)

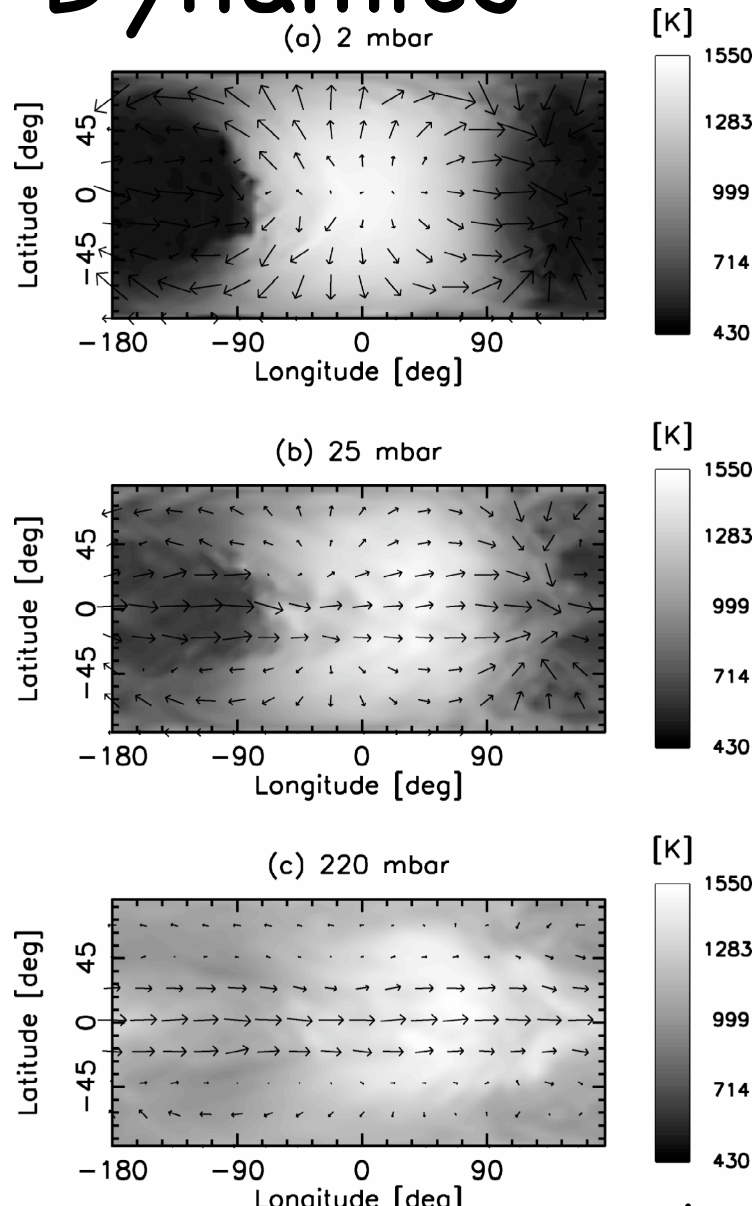
Questions?



Extra slides

Atmospheric Dynamics

- Predict hot spot near substellar point, gradual transition to colder night side
  - Cooper & Showman (2005,right), also Burkert, Langton, Koskinen
  - Stable thermal structure maintained by superrotating equatorial jet
- Some models predict polar circulation bands, polar vortices (Cho et al. 2003) - may be a problem with driven 2-D shallow water simulations
- No full coupling of spectral & atmospheric models yet (except Fortney et al. 2006)



peak speed: 10, 5, 3 km/s!!

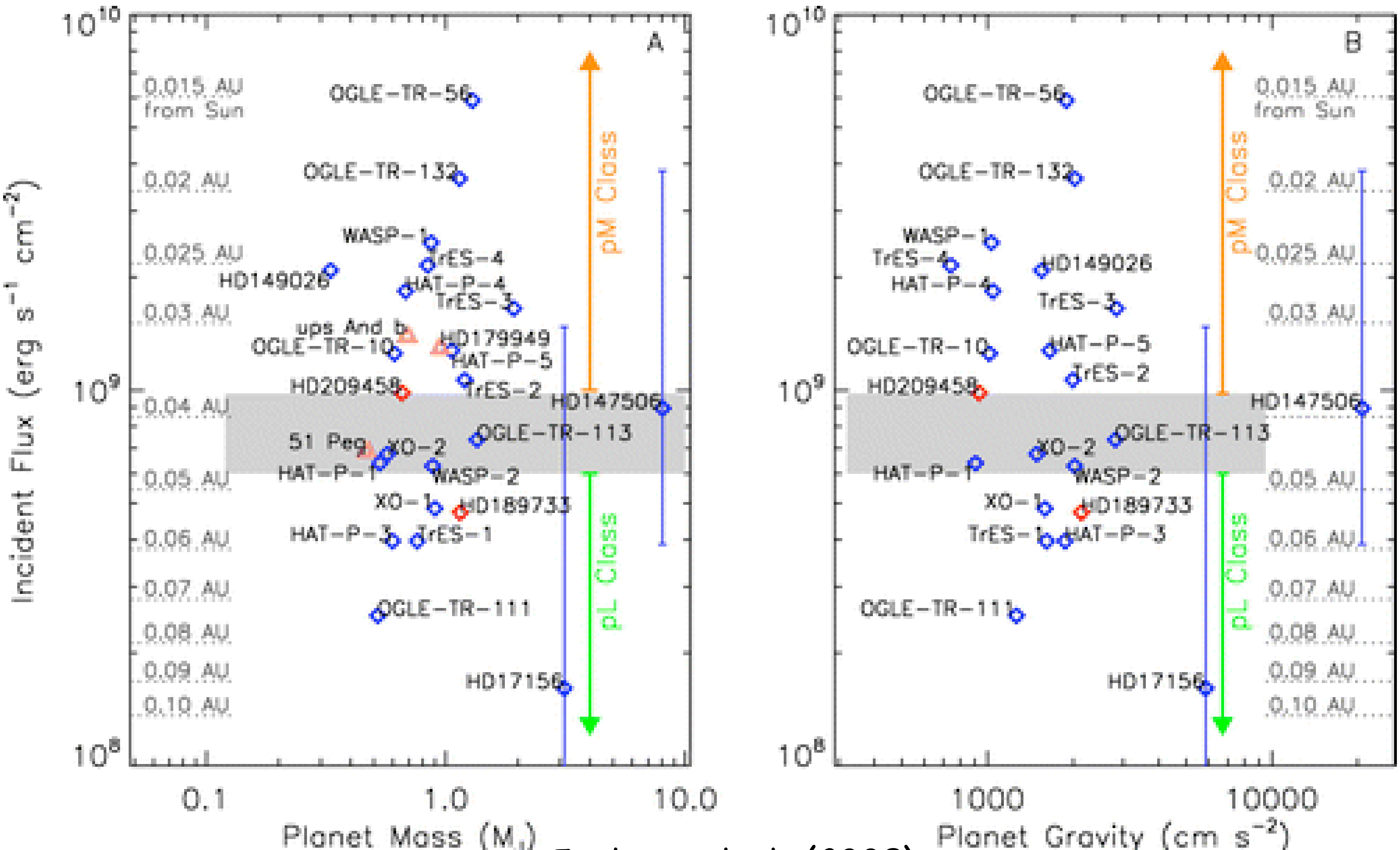
Two classes of hot jupiters?

Hubeny et al. 2003,
Burrows et al. 2007
Fortney et al. 2008

"pM" class	"pL" class
• higher insolation (<.05 AU)	• lower insolation (>.05 AU)
• higher TiO/VO opacity	• low/no TiO/VO opacity
• stratosphere (T inversion)	• decreasing temperature
Consequences:	Consequences:
• brighter day side	• fainter day side
• higher day/night contrast	• lower day/night contrast
• no phase-offseet	• phase offset
Ups And b, HD 149026 b, HD 179949 b	HD 189733 b

HD 209458 b, 51 Peg b

Two classes of hot jupiters?



Fortney et al. (2008)

Chromospheric variability?

- Two non-transiting systems have detectable phase functions: HD179949 and Upsilon Andromeda - both require low albedo, recirculation & inclination (naively)
- These are the **only** two systems studied by Shkolnik et al. (2005) to exhibit chromospheric (Ca H&K) activity with the planetary orbital period
- But, (1) out of phase with photometric variations; (2) intermittent activity
- Better to look at transiting planets...